SSC-370

UNDERWATER REPAIR PROCEDURES FOR SHIP HULLS (FATIGUE AND DUCTILITY OF UNDERWATER WET WELDS)

SHIP STRUCTURE COMMITTEE

1993

Member Agencies:

United States Coast Guard
Naval Sea Systems Command
Maritime Administration
American Bureau of Shipping
Military Sealift Command
Transport Canada

Ship Structure Committee

An Interagency Advisory Committee

Address Correspondence to:

Executive Director
Ship Structure Committee
U. S. Coast Guard (G-MI/R)
2100 Second Street, S.W.
Washington, D.C. 20593-0001
PH: (202) 267-0003
FAX: (202) 267-4677

SSC-370
SR-1333

February 7, 1994

UNDERWATER REPAIR PROCEDURES FOR SHIP HULLS (FATIGUE AND DUCTILITY OF UNDERWATER WET WELDS)

The use of underwater welding for the repair of damage below the waterline of a ship or marine structure has developed greatly in recent years. However, these procedures have generally only been acceptable as emergency repairs and temporary. Uncertainties with regard to the long term properties of the repairs have prevented a greater acceptance. This report addresses specifically the fatigue performance and low tensile elongation properties of underwater wet weld repair methods. The report concludes with recommendations for future research.

A. E. HENN
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

Technical Report Documentation Page

1. Report No. SSC-370	2. Government Accession No. PB94-121936	3. Recipient's Catalog No.
4. Title and Subtitle "Underwater Repair Procedures for Ship Hulls (Fatigue and Ductility of Underwater Wet Welds)"		5. Report Date May 1993
		6. Performing Organization Code
		8. Performing Organization Report No. SR-1333
7. Author(s) Grubbs, Kim and Zanis, Charles		
9. Performing Organization Name and Address CASDE Corporation 2800 Shirlington Road, Suite 600 Arlington, Virginia 22206		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DTCG23-90-C-20005
12. Sponsoring Agency Name and Address Ship Structure Committee U.S. Coast Guard 2100 Second Street Washington, D.C. 20593		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code G-M

15. Supplementary Notes

Sponsored by the Ship Structure Committee and its member agencies.

16. Abstract

Commercial ships may experience damage below the waterline from a variety of causes. Due to the significant costs and the time-consuming nature of unscheduled or emergency drydocking of a ship for repair, there is a clear need for the development of alternate repair methods which preclude having to drydock the ship. An area of ship repair which has the potential to accomplish this objective involves the use of underwater wet welding. A large amount of testing has been performed in recent years to characterize the properties of underwater wet welds, and indicates that this repair method has promise. This project addresses two significant technical areas relating to wet welds: 1) fatigue performance and 2) low tensile elongation properties of wet welds.

Fatigue performance was evaluated by testing underwater wet butt welds fabricated in 3/8-inch ASTM A 36 steel, using E7014 Type electrodes. The underwater wet welds were fabricated in fresh water at a depth of 30 feet, using a wet welding procedure qualified to the standards of ANSI/AWS D3.6-89, for Type B welds. Fatigue testing was performed on transverse weld specimens, with and without backing bars, subjected to cyclic axial tensile loading.

Findings indicated that 1) The S-N data for the underwater wet welds without backing bars have fatigue strength levels comparable to dry surface welds, and 2) the mean fatigue life of underwater wet weld specimens with backing bars was found to be about 50% lower than the mean fatigue life of specimens without backing bars. (Over)

17. Key Words Wet Weld, Fatigue, Ductility, Elongation, E7018, Strain, S-N Curve	18. Distribution Statement Distribution Unlimited, Available from: National Technical Information Service Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	82	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

Abstract (Continued)

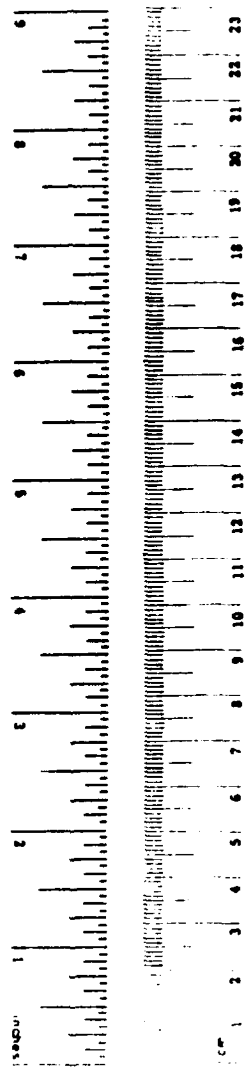
With regard to the relatively low tensile ductility of wet welds (6 to 8%), finite element analyses indicated that: 1) Wet butt welds in structural panels that are no closer than about 6" to frames or bulkheads should have adequate tensile ductility to withstand deformations typical of those encountered in service 2) Wet butt welds in structural panels that traverse frames or bulkheads do not appear to have adequate weld metal ductility to withstand deformations typical of those encountered in service 3) For welding of structure other than plate panels (such as hull inserts, brackets, etc.), detailed analysis of the weld region should be performed to ensure that strains in excess of 6% in the wet weld will not be encountered under normal operating conditions.

Recommendations for future study include the evaluation of fracture and fatigue performance of underwater wet welds containing defects, and the evaluation of the in-service performance of underwater wet welds on a commercial ship.

METRIC CONVERSION FACTORS

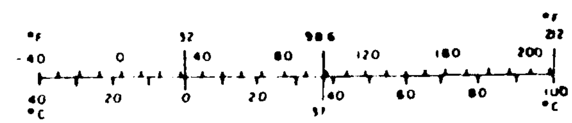
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



METRIC CONVERSION FACTORS

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES
(Continued)

SECTION 1.0
INTRODUCTION

1.1 GENERAL

Welding of commercial ship structure below the waterline may be necessary for a number of reasons, such as ship alterations and modifications, or the need to repair damage due to corrosion, accidents, severe cases of in-service loading, etc. If these welding operations are performed below the waterline, the traditional method for carrying out the work has been to take the ship into drydock. In the case of damaged ship structure which must be repaired, the significant costs and the time-consuming nature of unscheduled or emergency drydocking of a ship point out the need for the development of alternate repair methods which preclude having to drydock the ship. Any such repair method should be able to effect structurally sound permanent or semi-permanent repairs. In contrast to a temporary or emergency repair, which requires immediate docking of the ship, a semi-permanent repair is defined as a repair that keeps the ship in service until its next regularly scheduled drydocking. The repair method must be rapid and cost effective, and the quality of the repair must be such that the ship can continue its normal schedule of duties until its next regularly scheduled drydocking, which may include periods up to three years. Underwater wet welding is a method which has potential to effect sound permanent or semi-permanent repairs.

Wet welding for structural repair has been in use for some time in the offshore oil industry, and in the repair of pierside structures. The success of such repairs has led to an increased interest in the possible use of wet welding in the repair of ship structure (both commercial and military). A number of comprehensive programs have been undertaken in the past decade by agencies such as the American Welding Society, the Ship Structure Committee, and the U.S. Navy, with the intent of developing *minimum standards of* performance and workmanship, and determining the suitability of underwater wet welding for ship repair.

Considerable work has been performed in previous research programs devoted to the study of underwater welding (both wet and dry habitat). These programs have contributed greatly to the present understanding of the limitations and benefits associated with wet welding. The development of new and better wet welding techniques and materials, the quantifying of wet weld mechanical properties, the establishment of specifications for wet welding, and the development of procedure and performance standards have all resulted from the work undertaken in these programs.

1.2 OBJECTIVES

This report is one of a series of Ship Structure Committee (SSC) reports which seeks to quantify the characteristics of underwater wet welds, and to determine the feasibility of using wet welding methods for commercial ship repair.

The specific objectives of this SSC report are to:

1) Determine the S-N fatigue properties of underwater wet butt welds, and compare with the fatigue properties of dry surface butt welds, and

2) Evaluate the influence of low weld metal ductility on the structural performance of underwater wet welded ship structures.

Both of these areas have received little attention in previous investigations, and must

be addressed prior to recommending the use of underwater wet welding for repair of commercial ship structures.

1.3 APPROACH

The approach taken to accomplishing the above objectives involved the performance of a number of discrete subtasks. These subtasks were:

- Performance of a literature survey. This survey was performed to gather information on ship repair methods, the current state of knowledge concerning underwater wet welding, fatigue design and testing methodologies, and the relevance of ductility in ship structural design.
- Fabrication and testing of underwater wet welded fatigue specimens to establish high cycle fatigue properties, and comparison of results with existing surface air weld fatigue data.
- Finite element modeling and analysis of "typical" ship plate panels subjected to localized loadings and to uniform full surface pressure loadings, to establish the response of the low ductility wet weld.

1.4 REPORT ORGANIZATION

This report has been organized in the following manner:

Section 1.0 - Introduction and Statement of Objectives.

Section 2.0 - Literature Survey/Background Search. This section details the results of the literature survey. Subsections cover Current Ship Repair Methods (Section 2.1), Underwater Welding (Section 2.2), Wet Weld Mechanical Properties (Section 2.3), Fatigue Considerations in Welded Ship Structures (Section 2.4), Fatigue Testing Considerations of Welded Joints (Section 2.5), and Weld Ductility (Section 2.6).

Section 3.0 - Methodology. This section describes the testing and analysis methodologies used in this project. Section 3.2 describes the fatigue testing program undertaken in this project, and Section 3.3 describes the finite element analyses used to examine the effects of low weld ductility on structural performance.

Section 4.0 - Discussion of Results. This section presents and discusses the results of the fatigue and ductility studies conducted in this report.

Section 5.0 - Findings and Recommendations. This section summarizes the findings of the work performed in this study. This section also presents recommendations for future research products necessary to fully characterize the structural performance of wet welds, and to qualify their use in the repair of commercial ship structures.

Section 6.0 - Acknowledgements.

Appendices

References and Bibliography

SECTION 2.0
BACKGROUND

2.1 CURRENT SHIP REPAIR METHODS

Welding of commercial ship structure below the waterline may be necessary for a number of reasons, such as ship alterations and modifications, or the need to repair damage due to corrosion, accidents, etc. Traditionally, welding of commercial ship structure below the waterline has required drydocking of the ship so that welding can be performed in a dry surface environment. The welding operation follows documented work packages, and the fabrication methods, inspection techniques, and approval criteria are guided by various military or commercial standards and specifications developed for ship structures. The specific standards to which the welding operation will be performed will depend on the requirements of the customer for whom the work is being performed, and the regulatory body or organization which has approval authority for the particular ship (such as the American Bureau of Shipping, the U.S. Coast Guard, the U.S. Navy, etc.). In the case of repair of damaged ship structure, underwater welding methods, such as dry habitat welding or wet welding, have been allowed only in extreme emergencies (i.e., if the loss of the ship is possible), and have been considered to be temporary measures designed to get the ship to drydock. Once in drydock, the underwater repair is replaced with a more permanent surface welded repair.

The drawbacks to this traditional method of ship repair can be enormous in terms of cost and time. The schedule of the damaged ship is obviously affected by having to undergo an unscheduled drydocking, with the attendant monetary loss associated with having the ship taken out of service for the duration of the repair operation. These costs are in addition to the costs associated with the drydocking and repair operation itself. Additionally, other ship schedules may be disrupted in order to accommodate the damaged ship, further adding to the overall repair costs.

In view of these factors, using underwater wet welding for repairs to keep ships in service is an economically attractive option. Any repair technique that avoids having the ship perform an unscheduled drydocking operation generates significant cost savings in terms of minimal disruption of ship schedules and the avoidance of drydock fees. Wet welding repairs performed on offshore oil platforms have been shown to result in significant cost savings, even when compared with dry habitat welding repairs. In at least one case, repairs of similar types of damage on offshore oil platforms, performed in the same year, demonstrated that wet welding techniques can reduce costs by a factor of eight, in comparison with dry habitat welding [1].

2.2 UNDERWATER WELDING

2.2.1 Benefits of Wet Welding for Ship Repair

As defined by the American Welding Society in its document ANSI/AWS D3.6 ("Specifications for Underwater Welding") [2], underwater welding is "any welding performed below the water's surface", and encompasses both underwater wet welding and dry hyperbaric (dry chamber) welding.

This report deals only with underwater wet welding, and does not address dry habitat welding. While extensive work has been performed to characterize the properties and behavior of dry habitat welds, wet welding techniques offer cost and time saving advantages, specifically:

- Wet welding is more versatile, allowing access to restricted areas which are not easily accessible to dry habitat-type environments.

- The welding and support equipment needed for wet welding is fairly standard and can be quickly mobilized to a work site.

- Repair operations are more easily planned and executed due to welder accessibility.

Each of the above factors contributes to minimizing the time that a damaged ship is out of service, resulting in cost savings. Although the eight to one cost savings mentioned earlier may be extreme, wet welding repair costs have generally been shown to be about half as expensive as similar dry habitat repairs, when welding at depths of 50 feet or less [2].

Most underwater wet welding today is accomplished using the Shielded Metal Arc Welding (SMAW) process. The SMAW process is by far the most mature wet welding process in all aspects, including available filler materials, property characterization, and actual production use. Other processes exist, but their use has been very limited, and relatively little documentation is available about related properties, filler materials, or usability.

2.2.2 Traditional Concerns Associated with Wet Welding

The low esteem in which wet welding has long been held stems mainly from the poor quality (characterized by inferior or substandard mechanical properties) and unsuccessful performance observed in wet welded structures fabricated in the past. The poor quality of early wet welds is generally attributable to the use of marginal materials and inadequate wet welding techniques. Factors such as the use of surface electrodes simply coated with a waterproof material for wet welding and poor welder/diver training in wet welding techniques have contributed to the generally inferior performance observed in past wet welding applications. However, the development of improved wet welding procedures, including materials and quality control methods, have resulted in improvements in the quality and soundness of wet welds.

2.2.3 Essential Variables for Performance and Procedure Qualification

Studies of underwater wet welding have demonstrated that, in order to produce quality wet welds, it is essential that procedures for welding and training be strictly followed. Each welding procedure is defined by a number of welding parameters, or essential variables, which are used to ensure that a particular wet welding technique produces a sound weld. These essential variables include the base material and filler metal used, the electrical parameters of the welding arc, the welding technique, and the environment. These essential variables are discussed in detail in ANSI/AWS D3.6. Once the essential variables have been defined for a particular procedure, they may <u>not</u> be changed without invalidating the procedure. If a change occurs in any of the essential variables outside of the ranges specified in the procedure specification, this essentially creates a new procedure, which must then undergo the procedure qualification process. In order to fabricate a wet weld which meets acceptable levels of quality and workmanship, it is essential that the guidelines set forth in a qualified wet welding procedure are strictly followed.

After defining the essential variables of a wet welding procedure, the procedure is qualified for production work by extensive testing of weldments fabricated under real or simulated production site conditions. Procedure qualification requires both nondestructive testing (including visual, radiographic, and magnetic particle testing) and destructive testing

(including reduced section and all-weld-metal tensile testing, fillet weld shear testing, root-, face-, and side-bend testing, weld metal chemical analysis, and weld metal and HAZ Charpy impact testing). These tests are performed in order to ensure that the welding procedure is capable of producing high quality welds with acceptable mechanical properties and minimal defects. The particular tests performed and the number of test specimens required depend upon the joint design and welding technique used [2].

In addition to qualification of wet welding procedures, it is essential that all personnel engaged in wet welding production work be qualified to perform the particular welding procedure in production. It cannot be assumed that a person qualified to perform a particular type of weld in the dry will be able to perform acceptable quality welding in the wet. AWS D3.6 provides guidelines for evaluating the welder/diver's ability to fabricate sound welds using a particular welding procedure. As with qualification of the welding procedure, there are a number of essential variables for welder performance qualification, and a change in any of the essential variables between qualification testing and production conditions requires that the welder/diver be requalified to account for these differences. A change to any of the following essential variables for performance qualification will require that the welder/diver requalify for the welding procedure under the new conditions [2]:

- Welding mode (dry chamber, wet, habitat,etc.)
- Welding process.
- Change in AWS electrode classification or type.
- Change in welding position (flat, horizontal, vertical, or overhead), beyond specified limits.
- Change in base plate thickness, beyond specified limits.
- Omission of backing bar, but not vice versa.
- Change in type of diving suit protection.
- Increase in depth, beyond specified limits.
- Substantial degradation of visibility conditions.
- Increase in severity of environmental conditions to a point where welder/diver performance is affected.

The purpose of the preceding discussion has been to emphasize that the production of "sound" or "quality" wet welds is heavily dependent on the proper application of qualified procedures executed by qualified personnel. In general, the tolerances associated with the essential welding variables are tighter than those associated with surface air welds, and the skill required by the welder/diver is of paramount importance.

2.3 PROPERTIES OF WET WELDS MEASURED IN PREVIOUS STUDIES

2.3.1 Naval Sea Systems Command (NAVSEA) Underwater Welding Program

As mentioned earlier in this report, a number of activities in the past decade, spurred on by the successful use of wet welding in the offshore petroleum industry, have instituted research and development programs focusing on underwater welding for ship repair. An extensive amount of work has been conducted in this area by the Naval Sea Systems Command (NAVSEA). The NAVSEA program has examined both underwater wet and dry habitat welding for a variety of steels typically used in the construction of U.S. Navy surface ships and submarines. As this report is focused on the evaluation of wet weld properties and the suitability of wet weld repairs for commercial ships, dry hyperbaric welding will not be discussed in detail in this report.

The NAVSEA Underwater Welding Program has included, among other areas of study:

- electrode evaluation
- development of qualified procedures and welder/diver qualification criteria
- determination of underwater weld mechanical properties
- development of training programs for welder/divers
- examination of inspection methods and approval criteria
- development of standards and specifications for underwater welding on U.S. Navy surface ships.

Part of the NAVSEA program included an extensive evaluation of commercially available electrodes for use in wet welding repair work [3,4]. All wet welding was performed using the shielded metal arc welding (SMAW) process, which is commonly used by commercial diving companies in underwater repair. A survey of wet welding electrodes that are commercially available from U.S. sources was first conducted to identify and evaluate potentially suitable electrodes for use on U.S. Navy ships. These electrodes, which included AWS E7014, E309-16, E310-16, and E6013 type electrodes, were purchased from commercial vendors. Initial screening tests were performed with each of the electrodes to identify the best performing electrodes in terms of weldability and quality (as determined by nondestructive examination). The best performing electrodes from the initial screening tests were then used to produce 3/4" thick butt weld joints in a test tank for more rigorous testing. Base metal included ASTM A36 steel, and welding was performed in seawater at depths of 7 and 33 feet, in a variety of weld positions.

Testing of wet welded joints included visual, radiographic, dye-penetrant, reduced section tensile testing, side bends, macroscopic examinations, Vicker's hardness testing, all-weld-metal tensile testing, weld metal chemical analyses, and Charpy V-notch testing (weld metal, base metal, and HAZ). Testing and inspection was performed in accordance with criteria outlined in applicable military specifications and standards governing the fabrication and inspection of welded structures on U.S. Navy ships and AWS D3.6.

This testing identified two commercial wet welding electrodes as being capable of producing superior quality wet welds. Table 2.1 summarizes the average wet weld mechanical properties determined through this phase of the Underwater Welding Program, for one electrode at 33 FSW. To provide some perspective on the magnitude of the wet weld properties, properties for dry surface welds fabricated in the program are listed for comparison.

Table 2.1 Weld Mechanical Properties (NAVSEA Underwater Welding Program)

Weld Type	Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Average Charpy Toughness at +28° F (ft-lb) (NOTE 1)
Wet Hyperbaric (E7014 Electrode)	80.0	73.0	7.1	29.8 (80-100% shear)
Dry Surface	82.5	70.0	30	126.3 at (+30° F)

NOTE 1: HAZ toughness for all electrodes tested ranged from 28-61 ft-lbs. at +28° F. Average toughness of ASTM A36 base metal used was 75.5 ft-lbs at +28° F.

From the initial phase of the electrode evaluation program, the following conclusions concerning wet welding were drawn [3]:

- Weld metal tensile and yield strengths exceeded those of the ASTM A36 base plate.
- Wet weld metal elongation was less than that of E7014-type air weld metal. However, the wet welds consistently passed 4T bend tests, which are more stringent than the 6T bend tests required by AWS D3.6 for Type B welds.
- Weld metal Charpy toughness was in the range of 30 ft-lb at +28° F.
- Welds consistently met AWS D3.6 radiographic requirements for Type B welds, and often met more stringent Navy requirements.
- Results of welding and testing in open water under production conditions were essentially the same as results achieved in the test tank welding.

More extensive welding and testing was then undertaken in open water, with the electrode which yielded the best test results. This was performed to complete the requirements necessary for qualification and to ensure repeatability of results under production conditions. Similar mechanical property test results were obtained, along with 5/8" dynamic tear toughness test results (at +28° F), which are summarized as follows:

- Weld Metal: 187-324 ft -lbs
- HAZ: 95-280 ft-lbs
- Base Metal (ASTM A36): 73-80 ft-lbs

In the paper describing their work, presented at the 70th Annual AWS Meeting in 1989, Mitchell, West, and Lindberg concluded that underwater wet welds can be fabricated with a high degree of structural integrity, such that "the use of wet welding can be justified for limited applications in U.S. Navy surface ship repair" [4].

The good properties and weld soundness obtained from wet welding in the NAVSEA Underwater Welding Program has led to implementation of wet welding repairs for limited applications on U.S. Navy surface ships. These repairs, presently being performed on U.S. Navy ships include, but are not limited to, waster sleeve and sea chest scoop repair, bilge keel and fairwater repair, rope guard and padeye repair, and landing ship bow and stern gate stop repair. The application of wet welding techniques to repair other types of underwater damage to Navy ships is evaluated on a case by case basis, as the damage occurs. The main impediment to qualification of wet weld repair techniques for more far-ranging repair situations is the stringent weapons effects resistance criteria which U.S. Navy ships must meet.

Based upon the above findings, as well as program results and "lessons learned" during the Underwater Welding Program, the U.S. Navy has developed draft specifications and standards to be used as guidance documents in the implementation of underwater welding techniques for repair of U.S. Navy surface ships. Currently undergoing review, these documents will provide standards governing underwater welding procedure and performance qualification, as well as inspection methods and approval criteria, which must be adhered to when implementing underwater welding for repair of U.S. Navy ships.

2.3.2 Southwest Research Institute Study (for Ship Structure Committee)

A Ship Structure Committee task performed by the Southwest Research Institute (SwRI) was aimed at evaluating the mechanical properties of underwater weldments, and evaluating the feasibility of using wet and wet-backed welds in ship repair. The program is detailed in SSC Report 335 [5], and the conclusions are summarized here.

Table 2.2 lists representative tensile strength, yield strength, and elongation properties of 1-inch thick wet butt welds fabricated in the SwRI program. These welds were fabricated using E6013 electrodes in ASTM A 36 base metal, and are seen to be similar to the properties measured in the NAVSEA program (Table 2.1).

The SwRI study also determined the fracture toughness (K_{Ic}, derived from J_{Ic}) of wet welds fabricated in 1-inch thick steel. Wet welds fabricated at 33 foot depths were found to have a weld metal fracture toughness greater than 93 ksi-in$^{1/2}$, and initial values of CTOD greater than 0.0034 inch. A fracture mechanics analysis performed in the SwRI study revealed a tolerable defect size of about 1-inch in the presence of stresses as high as the yield strength of the weld metal, or about 1/4-inch in the presence of twice the minimum yield stress. This fracture toughness was found to be sufficient to tolerate flaws larger than those allowed under ANSI/AWS D3.6 (1/8 inch) under stresses as high as the minimum str of the weld metal.

Based on the results of the testing performed in the program, the SwRI study concludes that the "wet and wet-backed metal arc welding (SMAW) process can produce welds suitable for structural applications", and "should be allowed on marine structures where presently prohibited by companies and regulatory agencies" [5].

Table 2.2 Wet Weld Mechanical Properties at 33 Foot Depth (SSC Report 335)

Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Average Charpy Toughness at +28° F (ft-lb)
78.2	71.6	9.4	33 (100% shear) (NOTE 1)

NOTE 1: HAZ toughness at +28° F = 8 ft-lbs (10 ft-lbs from surface dry weld HAZ in this plate).
For 1/2-inch butt weld, HAZ toughness at +28° = 55 ft-lbs (55 ft-lbs from surface dry weld HAZ in this plate).

2.3.3 Colorado School of Mines Study

Work conducted by the Colorado School of Mines [6] was directed at evaluating crack propagation rates of underwater wet welds vs. dry surface and dry habitat welds. This study showed that the fatigue crack growth rates of weldments are highly dependent on the porosity of the weldments. High quality, low porosity underwater wet welds fabricated with E6013 electrodes in A36 steel demonstrated fatigue crack growth behavior which was similar to that of dry surface welds and dry habitat welds. A follow-up study conducted by the Colorado School of Mines [7] demonstrated that the fatigue crack propagation characteristics of underwater wet welds tested in seawater are similar to those for wrought steel in seawater. Specifically, this study showed that:

- A decrease in loading frequency results in an increase in crack growth rate for all values of stress intensity factor.
- At low stress intensity factors and high frequency (30 Hz), crack propagation rates for underwater wet welds tested in seawater were substantially less than for underwater wet welds tested in air.
- At high stress intensity factors and high frequency (30 Hz), crack propagation rates for underwater wet welds tested in seawater were greater than for

underwater wet welds tested in air.

These studies concluded that "underwater wet welding procedures produce fatigue resistant weld metal that is adequate for use at low applied stresses in offshore structures" [7].

2.4 FATIGUE CONSIDERATIONS IN THE DESIGN OF SHIP STRUCTURES

An area of study which has not yet received much attention, and which is extremely important in the design of ship structures, is the fatigue characterization of wet welds. In larger ships, especially, fatigue can be a critical problem. Reports from the proceedings of the 7th International Ship Structures Congress [8] show that about 70% of the total damage in ships over 650 feet in length may be classified as fatigue damage. For ships under 650 feet in length, fatigue damage accounts for only 20% of the total damage. Since excessive fatigue cracking in ship structures can lead to failure, it is imperative that any repair work performed on ship structures be evaluated for fatigue failure resistance.

Numerous laboratory studies and research and development projects conducted over the years have demonstrated that, in addition to the obvious importance of the weld quality, there are three main factors which can affect the fatigue characteristics of welded joints [9]. These are:

1) Member geometry. This category includes both the overall configuration of the welded structure and the local geometry of the weld design.
2) The types and intensities of loading to which the welded member is subjected. Included in this category are constant amplitude cyclic loading, random loading, loading frequency, etc.
3) The materials (both base material and filler metal) from which the welded joint is fabricated.

Specific details of the relative importance of each of the aforementioned factors in the fatigue strength of welded structures have been discussed in numerous previous references [10, 11], and will not be reported in detail here. It is important, however, to understand that the fatigue performance of a welded structure is affected by numerous factors, and a designer must ensure that each of these factors is fully understood and accounted for in any design of a welded structure.

Fatigue behavior of structural details is generally evaluated in constant-cycle fatigue tests, and the results presented in S-N diagrams relating the level of loading to the number of cycles to failure. These S-N curves are generally plotted on a log-log basis, and each S-N curve is applicable only to a particular type of detail and loading; the results of one S-N curve are not directly transferable to different detail geometries or loading patterns. Thus, it is important that the member geometry and expected service loading for a structural detail be thoroughly examined and understood before an existing S-N diagram is applied to design of the detail.

Application of laboratory fatigue data to actual ship design is a complex subject relying heavily on statistical evaluation of laboratory data and predicted ship loadings, and the application of appropriate reliability functions and safety factors. Reference 12 provides an excellent discussion of various methods used to reduce laboratory fatigue data to a usable form, and the application of that data to design of ship structural details. Since the determination of reliable methods for the application of existing fatigue data to ship design is not the focus of this project, and has been well documented in previous studies, it will not be covered here.

2.5 FATIGUE TESTING OF WELDED CONNECTIONS

As with the application of fatigue data in the service design of ship structures, the generation of fatigue data through testing and analysis is dependent on a number of different factors. These factors, relating to the fabrication, preparation, and testing of fatigue specimens, must be carefully controlled if meaningful results are to be generated. These factors, and their relative importance in fatigue testing experiments, are discussed in this section.

Almost all previous studies agree on the point that the weld geometry is one of the most important factors governing the fatigue strength of welded specimens. It has been shown in numerous studies using a variety of electrodes and base materials that the presence of a weld "reinforcement", or weld crown, significantly decreases the fatigue strength of a welded specimen [13]. The abrupt change in geometry at the base plate/weld toe interface acts as a stress raiser which initiates cracking at the weld toe. The reentrant angle determines the degree to which the fatigue properties of the weldment are reduced.

Studies have shown that the presence of a backing bar, which is typically left in place in an actual repair, affects the fatigue properties of a butt weld in much the same way as the weld crown. The abrupt change in geometry created by the backing bar reduces the fatigue strength of the welded joint [11]. Fillet welded backing straps welded to structure to increase the strength of the structure have been shown to have a detrimental effect on the fatigue life of the structure.

Residual stresses present in welded joints have been shown to affect the fatigue strength of the joints, but this effect is difficult to quantify. Studies have shown that the effects of residual stresses may differ from one instance to another, depending upon the materials and geometry of the members, the state of stress, the magnitude of the applied stress, the type of stress cycle, and other factors. Munse [10] has stated that the effect of residual stresses on the fatigue strength of transverse butt welded specimens is minimal. Pollard and Cover [14] have stated that residual stresses only affect fatigue strength in cases of alternating loads, while Ross [15] has suggested that residual stress effects can be ignored. Other studies, however, have emphasized the effect of residual stresses on both increasing and decreasing the fatigue life of welded specimens. Since residual stresses are virtually impossible to eliminate, and difficult to measure accurately, their effect is frequently ignored in fatigue studies. In general, it is felt that the presence of residual stresses upon the fatigue strength of welded structures is a second order effect, and is not as influential as the weld geometry [11].

Postweld treatments to relieve residual stresses present in welded structures, such as thermal stress relief and peening, have generally shown to be of limited value in increasing the fatigue strength of butt welded specimens [16].

Studies performed by the University of Illinois indicate that specimen size and base plate thickness have no significant effect on the fatigue characteristics of a butt welded plate. The specimen length is chiefly governed by the type of testing machine to be used, and also the relationship between the length of the specimen and other geometric characteristics of the specimen. Comparison of fatigue test results for single-vee butt welds fabricated in 1/2", 3/4", and 7/8" base plates have shown no significant variations in fatigue strength between specimens [17]. Comparison of additional test results utilizing specimens ranging in width from 1-3/8" to 6", and in base plate thickness from 1/2" to 1-1/2" indicate no significant variation in fatigue strength [14].

Previous studies have shown that the frequency (the rate of cyclic loading) at which

fatigue specimens are tested in air has little effect on the fatigue strength of the specimens, unless high frequency (above 100 Hz) testing is used [10]. This is a very important fact, as a major factor in the cost of a fatigue testing program is due to the residence time of the specimens in the testing machines. Therefore, if the testing frequency can be increased, it should be possible to test more samples and generate a larger data base without increasing costs significantly and without adversely affecting the test results.

Fatigue tests conducted with air welded specimens immersed in seawater have shown that the corrosive effects of the seawater lead to a degradation in the fatigue strength of uncoated welded joints [10]. This is obviously an important consideration in the fatigue design of ship structures when using data generated from testing of fatigue specimens in air. Coatings are therefore typically applied to welds fabricated for ship structures, in order to protect the welds from the corrosive effects of sea water. It has been shown that coatings applied to welded joints have some effect in counteracting this effect, but not all coatings have been found to be effective [14]. No studies were discovered in which coatings had a detrimental effect on the fatigue strength of welded structures.

The University of Illinois has compiled a Fatigue Data Bank to collate and tie together fatigue test results from numerous fatigue testing programs. This Fatigue Data Bank acts as a computerized repository containing the results of thousands of fatigue studies conducted over the years. By identifying key parameters (such as base plate yield strength, electrode specification type, etc.), the data from numerous test programs of similar scope is used to generate a single S-N curve. Testing parameters which are considered to be of secondary importance are ignored. The Fatigue Data Bank and its use are described in detail in Reference 18.

2.6 WELD DUCTILITY

As reported earlier, wet welds have typically been found to exhibit low weld ductility characteristics. In order to examine the importance of weld ductility in structurally critical areas of a surface ship, present ductility requirements were first investigated. The ductility requirements set forth by various design agencies for welding of ship structure are summarized below :

- For U.S. Navy surface ships, from MIL-E-0022200/10A [19], "Electrodes, Welding, Mineral Covered, Iron Powder, Low-Hydrogen Medium, High Tensile and Higher Strength Low Alloy Steels", Table III, weld ductility requirements are as follows:

Electrode Type	Minimum Elongation in 2 Inches
MIL-7018-M	24%
MIL-10018-M1	20%

- From AWS A5.5-81 [20], "Specification for Low Alloy Steel Covered Arc Welding Electrodes":

Electrode Type	Minimum Elongation
AWS E7018-X	25%

- From MIL-E-23765/2D [21], "Electrodes and Rods, Welding, Bare, Solid, or Alloy Cored, Low Alloy Steel", Table III, weld elongation requirements are as follows:

Electrode Type	Minimum Elongation in 2 Inches
MIL-120S-1	14%
MIL-120S-2	14%

- For U.S. Navy surface ship hull materials, from MIL-S-22698B [22], "Steel Plate and Shapes, Weldable Ordinary Strength and Higher Strength: Hull Structural", Section 3.8.1, it is required that "all grades of material shall be tested in accordance with ... and shall meet all mechanical properties specified in section 43 of the ABS Rules..."

- From ABS Section 43, Table 43.1 [23], ductility requirements for hull steels shall be as follows :

Steel Grade	Minimum Elongation Requirements
A,B,D,E,DS,CS	21% in 8 inches, or 24% in 2 inches
AH32,DH32,EH32	19% in 8 inches, or 22% in 2 inches
AH36,DH36,EH36	19% in 8 inches, or 22% in 2 inches

- From ANSI/AWS 3.6-89, "Specification for Underwater Welding", for Type A and Type O groove welds fabricated in base plate with a yield strength of up to 50 ksi, minimum required elongation is 19% For Type B groove welds, no elongation requirements are given. It should be noted that ANSI/AWS D3.6-89 defines Type A welds as "suitable for applications and design stresses comparable to their above-water counterparts by virtue of specifying comparable properties and testing requirements." Type B welds are "intended for less critical applications where lower ductility, greater porosity,.. can be tolerated." Type O welds "must meet the requirements of some designated code or specification, as well as additional requirements defined [in ANSI/AWS 3.6-89]..."

From the information summarized above, it can be seen that the standards require that the base materials and weld material used in ship structures have a minimum ductility of at least 14%. Wet welds have been shown to have about 6% to 8% elongation as measured

from all weld metal tensile specimens [3,4].

The lower ductility characteristic of wet welds could make them unsuitable for critical application on surface ships. However, the problem of low wet weld ductility has been addressed in Reference 5. The conclusion of this report was that, while low weld ductility was a serious problem, it was not insurmountable. This report states that "...through proper design, underwater wet welded repairs, attachments, and even original fabrication can be made such that the reserve ductility exhibited by dry welds is not required. The principle involves insuring that the structural member remote from the wet weld can become fully plastic before the applied stress (excluding residual stress) in the weld metal exceeds its yield strength". Reference 5 provides a proposed design procedure using wet welds, stated as:

> "The stress in the wet weld should not exceed F_y (where F_y is the yield stress of the base plate or weld metal, whichever is less) for tensile or compressive stress and 0.6 F_y for shear stress, under loading which would fully yield at least one member of the connection by either axial load, bending or torsional moment, shear or any combination loading, whichever combination creates the highest stress in the wet weld. Critical cross-sections perpendicular to the applied stress should not be composed entirely of wet weld (this precludes girth welds) and shall meet the above requirements."

For ship structure, this indicates that for structurally critical areas of a ship, proper design of the weld connection may allow the use of low ductility wet welds in the connection fabrication.

SECTION 3.0
PROGRAM METHODOLOGY

3.1 GENERAL

This section discusses the procedures used to fabricate and evaluate the fatigue properties of wet welds and discusses the procedures used to evaluate the potential effects of low wet weld ductility on ship structural integrity. Fatigue properties were determined for wet transverse butt welds fabricated in 3/8" steel, and subjected to cyclic axial tensile loadings. The wet welds were fabricated using commercially qualified wet welding methods in ABS Grade A36 steel, using BROCO UW-CS-1 Sof Touch wet welding electrodes (AWS type E7014). Welds were fatigue tested in the "as-welded" condition (i.e., with the weld reinforcement intact), both with and without a backing bar. A wet welded mechanical property test plate was fabricated in order to produce mechanical property test specimens for verification of wet weld tensile properties. In addition to the wet welds, a limited number of air weld fatigue specimens were fabricated and tested in order to validate the applicability of the baseline air weld S-N curve used for comparison purposes. In addition, the air welds were used to provide a direct comparison of air vs. wet weld fatigue performance in a controlled program.

The importance of low wet weld ductility on the performance of welded ship structures was evaluated using finite element models to analyze typical plate panels subjected to highly localized loadings and to uniform pressure loadings. The finite element program COSMOS/M was used to determine strain levels in loaded plate panels of varying aspect ratios and thicknesses.

3.2 FATIGUE TESTING

3.2.1 Specimen Design

The specimen design chosen for fatigue testing in this program was a flat, axial specimen with a transverse butt weld, subjected to constant amplitude tension-tension fatigue testing. This specimen type, identified as Specimen type 10 in Reference 12, represents a typical weldment used when joining two flat pieces of steel plate (such as hull plating) into a single structure. Such a technique might be used when removing a section of damaged hull plating and replacing it with undamaged plate, or when placing an insert into the hull.

One of the most important factors in determining the fatigue life of a welded specimen is the geometry of the specimen and the shape of the weld crown. All specimens in this study were tested in the "as-welded" condition (i.e., with the weld reinforcement intact).

3.2.2 Materials

All weldments used for the fabrication of fatigue specimens were prepared from 3/8" thick ABS Grade A36 steel plate, conforming to the criteria of MIL-S-22698. The wet welded mechanical property test weldment was prepared from 3/4" ordinary strength steel (OSS) plate conforming to MIL-S-22698. The carbon equivalent for the 3/8" plate was 0.264, and the carbon equivalent for the 3/4" plate was 0.316. One heat of steel was used for all fatigue specimen test plates, and the principal rolling direction of the steel was marked on all material. The manufacturer's certificates of inspection for these plates are included in Appendix A. Ordinary strength steel conforming to MIL-S-22698 was used for backing bars on all weldments. All material was selected to represent typical steel used in the fabrication of ship structures.

The electrodes used to produce all weldments in this task were BROCO UW-CS-1 Sof Touch (E7014 type), 1/8" diameter electrodes. These electrodes are one of the two commercially available electrodes found in the electrode evaluation program discussed in Section 2.3.1 to produce superior quality wet welds, and are frequently used by commercial diving companies. All electrodes used in this program were taken from the same lot and batch to ensure consistency in results. For fabricating air weldments, it was specified that some of the electrodes be delivered without the waterproof coating that is normally applied. The remaining electrodes were delivered with the BROCO-applied waterproof coating.

3.2.3 Selection of Baseline Air Curve

A data search was conducted to identify an existing S-N curve for air weld fatigue specimens fabricated with the same basic parameters to be used in the fabrication of the wet welds in this task. Numerous technical reports were reviewed in order to find a "baseline" air weld S-N Curve generated in a single project, but in most cases there were variations in the testing parameters which would have invalidated their use for comparison purposes with the results of this study. In the end, the Fatigue Data Bank at the University of Illinois was accessed in order to establish a baseline air curve.

The data on this curve was based on data from fatigue tests for surface air welds which utilized single-vee, full penetration transverse butt weld joint designs, fabricated from ABS Grade A base plate material with E7018 or E7014 type electrodes, and loaded with an applied axial load having an R ratio of 0 (zero to tension loading). The resulting S-N curve provided by the Fatigue Data Bank is shown in Figure 3.1. These results represent specimens tested with the weld reinforcement intact, and failure was taken to be the point at which complete separation of each specimen occurred. The equation of the linear regression best-fit curve for the air weld data shown in Figure 3.1 is:

$$S = 281.0638\ N^{-0.1572}$$

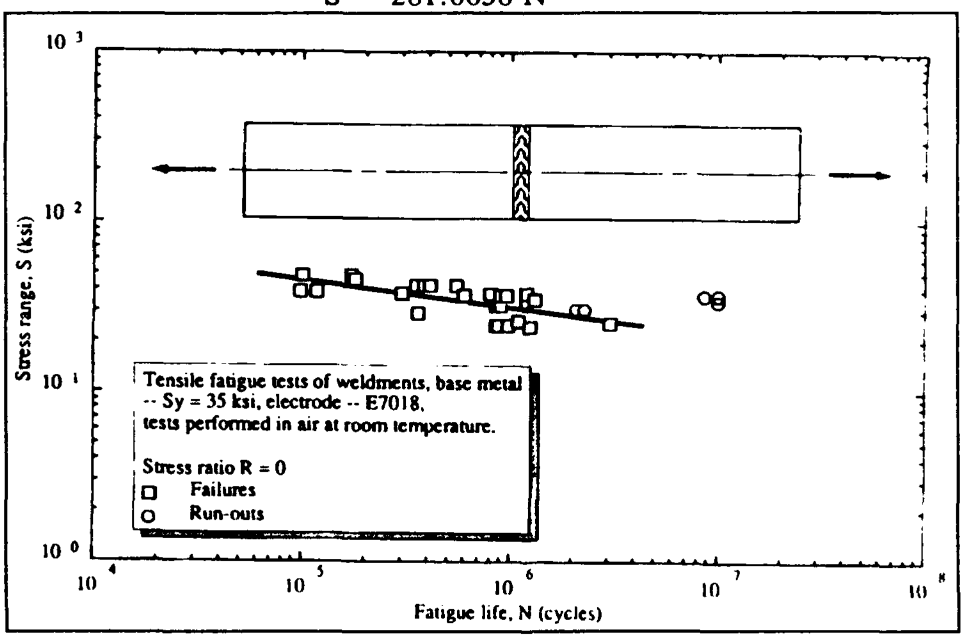


Figure 3.1 Baseline S-N Curve (Surface Air Weld)

3.2.4 Fabrication of Welded Test Plates

3.2.4.1 Welding Test Plan

The general outline of the welding plan used in this project is as follows:

- A 12" x 14" mechanical property test plate (hereafter designated as plate WWMP-PL1) was welded in the wet. All-weld-metal tensile test specimens and bend test specimens were taken from this plate to ensure that quality welds had been produced, and to ensure that properties were similar to wet weld properties obtained in previous studies. This also provided a quality check on the electrodes purchased for welding.
- A 6' x 2' x 3/8" steel plate (hereafter designated as plate AW-PL1) was fabricated in air using electrodes from the same lot as those used in the fabrication of the wet welds (but without the waterproof coatings). From this plate, air welded fatigue specimens were prepared and tested to verify that the baseline air S-N curve was representative of the basic electrode and weld joint design to be used in the wet weld fatigue tests.
- Two 6' x 2' x 3/8" wet welded test plates (hereafter designated as plates WW-PL1 and WW-PL2) were fabricated for preparation of wet weld fatigue test specimens.
- All weldments were subjected to visual, magnetic particle, and radiographic NDE to ensure that sound quality welds were obtained.
- Once welding was completed, the welded test plates were shipped to a machine shop for preparation of fatigue test specimens.

All welding (both air and wet) was performed by Global Divers of Houma, Louisiana. Global Divers is an experienced commercial repair company which has been actively involved in numerous welding research and development programs in the past. Global Divers was responsible for all material procurement and welding undertaken in this task. All welding took place at Global Divers' New Iberia, Louisiana facility. Mr. Tom West of Third Party Plus (formerly Welding Engineering Services) acted as CASDE Corporation's on-site representative in charge of all welding operations, responsible for the evaluation and approval of inspection results and welder qualification.

The following sections give a detailed description of the welding processes, procedures, fabrication, and inspection of the welded test plates.

3.2.4.2 Welder and Welding Procedure Qualification

All wet welding was performed in accordance with a Global Divers proprietary wet welding procedure, originally qualified for general underwater structural repairs for the Exxon Company; this procedure was subsequently qualified for NAVSEA to requirements exceeding those for ANSI/AWS D3.6 Type B welds. Dry welding procedures were qualified to MIL-STD-248 [24]. The joint design was a single-vee, full penetration, multiple pass groove weld with a backing bar, and the welding parameters employed in the fabrication of each test plate are detailed in Appendix B.

All welder/divers were required to be qualified to the requirements of ANSI/AWS D3.6 for the welding procedure used. The qualification of each welder/diver to perform the specified procedure was verified and approved by Third Party Plus prior to fabrication of project test plates.

Prior to welding of the any test plates, each welder/diver was required to wet weld a

6" long Confirmation Weld test plate. These Confirmation Welds were used to ensure that the welding system was functioning properly and that the welder/divers were able to use the system and procedure to produce quality welds. These plates were welded at a 30 foot depth and were required to meet the NDE acceptance criteria of the references listed in the following section.

3.2.4.3 Inspection Criteria

NDE of all weldments included visual inspection (VT), magnetic particle inspection (MT), and radiographic inspection (RT). All VT and MT of weldments was performed by Global Divers, and radiographic inspection was performed by Global X-Ray, located in Lafayette, LA. The welds were inspected over 100 percent of their length in accordance with the requirements of MIL-STD-271F [25] and were required to meet, as a minimum, the following acceptance criteria:

Air Welds:

- Visual inspection (VT) in accordance with Class 2 requirements of NAVSHIPS 0900-LP-003-8000 [26].
- Magnetic particle (MT) inspection in accordance with Class 1 requirements of NAVSHIPS 0900-LP-003-8000.
- Radiographic inspection (RT) in accordance with NAVSHIPS 0900-LP-003-9000, Class 3 [27].

Wet Welds:

- Visual inspection (VT) in accordance with Class 2 requirements of NAVSHIPS 0900-LP-003-8000.
- Magnetic particle (MT) inspection in accordance with Class 1 requirements of NAVSHIPS 0900-LP-003-8000.
- Radiographic inspection (RT) in accordance with NAVSHIPS 0900-LP-003-9000, Class 3, except that porosity less than 1/16 inch diameter was not restricted in number.

3.2.4.4 Fabrication of Wet Mechanical Property Test Plate

The design of the wet welded mechanical property test plate (WWMP-PL1) is shown in Figure 3.2. In fabricating weldment WWMP-PL1, the following steps were taken:

1) Two 6" x 14" x 3/4" OSS plates were fitted, and a backing bar was tack welded into place, as shown in Figure 3.2. Plate fit-up and tack welding of the backing bar were performed in air.
2) The tack welded 12" x 14" plate was positioned in the tank in the vertical position, at a depth of 30 FSW.
3) The plate was wet welded in the vertical down position using the approved welding procedure.
4) The weldment was removed from the tank. After removal of the weldment from the tank, MT and VT were performed over 100% of the weld length.
5) After satisfactory completion of VT and MT, the weldment was shipped to Global X-ray for radiographic inspection. RT showed that the weld fully met the acceptance criteria.
6) After successfully meeting the RT acceptance criteria outlined earlier, the weldment was shipped to PARTEK Laboratories for fabrication of all-weld-metal-tensile specimens and bend specimens. Specimens were prepared and tested in accordance

with ANSI/AWS 4.0 [28] and MIL-STD-248 [24].

The results of the mechanical property tests conducted by PARTEK Laboratories are included in Appendix C and the tensile test results are summarized in Table 3.1. These results show that the tensile properties of the wet welds produced in this program are comparable with properties reported in previous studies [3,5]. The four side bend specimens tested were acceptable when bent to a 4T radius.

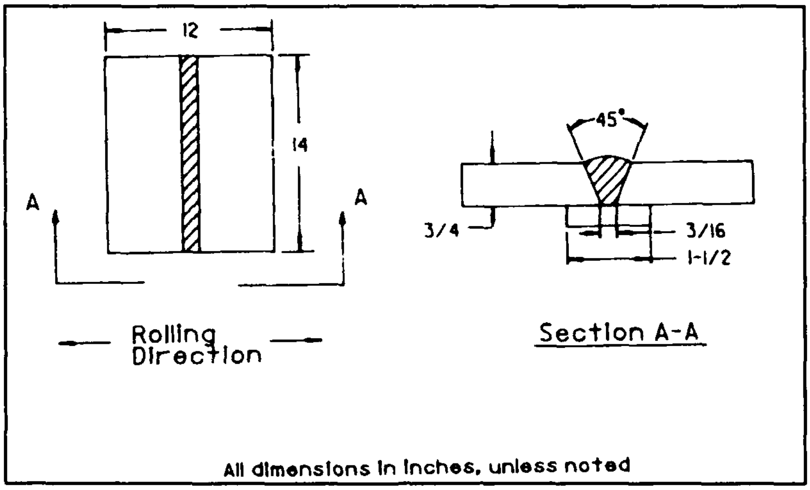


Figure 3.2 Mechanical Property Test Plate WWMP-PL1

Table 3.1 Results of All-Weld-Metal Tensile Tests of Wet Weldment WWMP-PL1

	Specimen Number 1	Specimen Number 2	Range of Values Observed in Previous Programs
Ultimate Stress (psi)	82,900	79,600	77,050 - 83,050
Yield Stress (psi)	77,100	74,200	70,900 - 76,550
% Elongation	7.4	6.4	6.0 - 8.3
Reduction in Area (%)	13.2	10.5	-

3.2.4.5 Fabrication of Air Welded Test Plate AW-PL1

The design of the air welded fatigue specimen test plate (AW-PL1) is shown in Figure 3.3. In fabricating weldment AW-PL1, the following steps were taken:

1) Two 72" x 12" x 3/8" plates were fitted in the vertical position. The backing bar was then tack welded into place. The backing bar for this weldment was produced from 1/4" thick plate, and had a width of 1-1/2", as shown in Figure 3.3.
2) Welding was performed in air using electrodes from the same lot employed for wet welding, but without the waterproof coating.

3) After welding, the plate was cut into two 36" x 24" x 3/8" pieces, as shown in Figure 3.3(b).
4) The backing bar was removed from one of the 36" x 24" x 3/8" pieces. MT was performed on the weld root for this piece, to ensure that the weld met the specified acceptance criteria. The weld root was then background as necessary and the weld was completed from the reverse side. VT and MT were then performed over 100% of the completed weld length. This 36" x 24" x 3/8" welded test plate was then designated as Weldment AW-PL1A.
5) The second 36" x 24" x 3/8" test piece (with the backing bar intact) was then stored for possible later use. Further use of this plate was not required.
6) After satisfactory completion of VT and MT, weldment AW-PL1A was radiographically inspected.
7) After satisfactory completion of all NDE, plate AW-PL1A was sent to a machine shop for preparation of fatigue specimens, as described in Section 3.2.5.

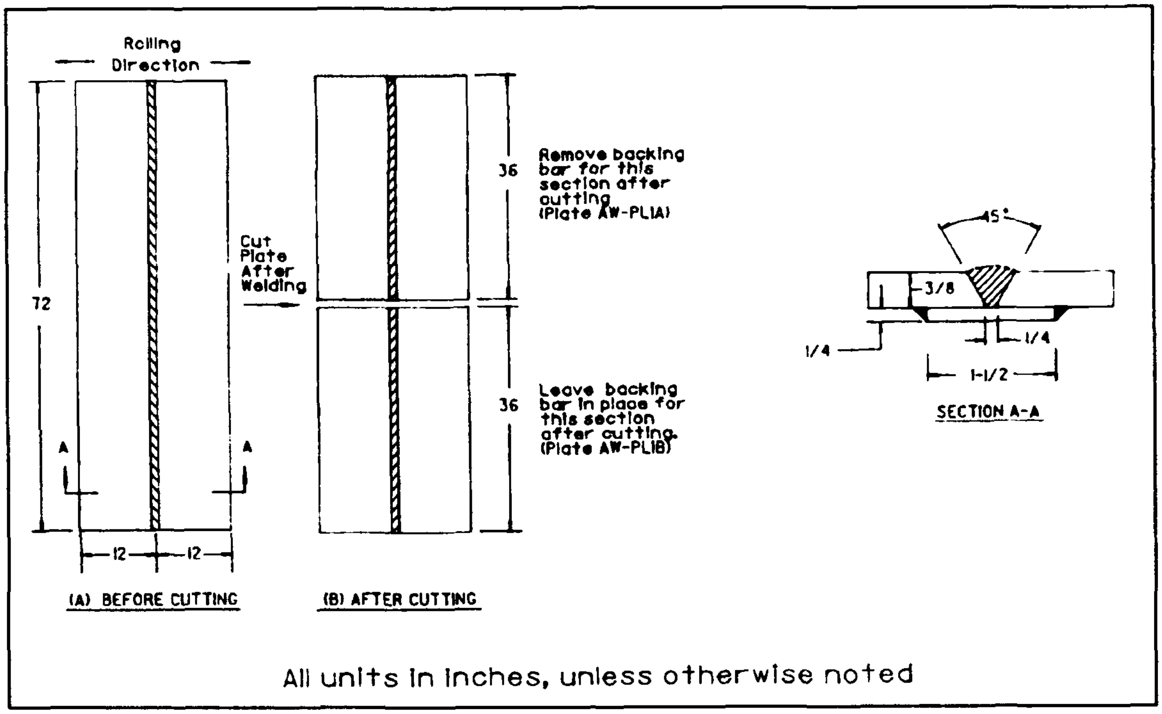


Figure 3.3 Air Welded Fatigue Test Plate AW-PL1

3.2.4.6 Fabrication of Wet Welded Test Plate WW-PL1

The design of the wet welded fatigue specimen test plate (WW-PL1) is shown in Figure 3.4. In fabricating weldment WW-PL1, the following steps were taken:

1) Two 72" x 12" x 3/8" flat plates were fit up with a 3/16" backing bar, as shown in Figure 3.4. Plate fit-up and tack welding of the backing bar were performed in air.
2) The test assembly was lowered into the fresh water diving tank, and welding was performed in the vertical position, at a depth of 30 FSW.
3) Following welding, the test plate was RT inspected before removal of the backing bar. RT indicated that there were minor slag accumulations in the weld at the weld root. Although the weld met the ANSI/AWS D3.6 requirements for Type B welds, it

did not meet the more rigorous acceptance criteria of NAVSHIPS 0900-LP-003-9000 (Class 3). Therefore, the backing bar was ground off and the weld root was background to remove these slag accumulations. In removing the backing bar from the plate, however, some material was accidentally removed from the base plate surrounding the weld. This resulted in the creation of a "notch" in the plate, approximately 1-1/2" wide, with a depth varying from 0" to 1/64". A sketch of the approximate geometry of this notch is shown in Figure 3.5. The steps taken to alleviate this condition before fatigue testing are discussed in Section 3.2.5.1 of this report, which deals with fabrication of fatigue specimens from the welded plates.

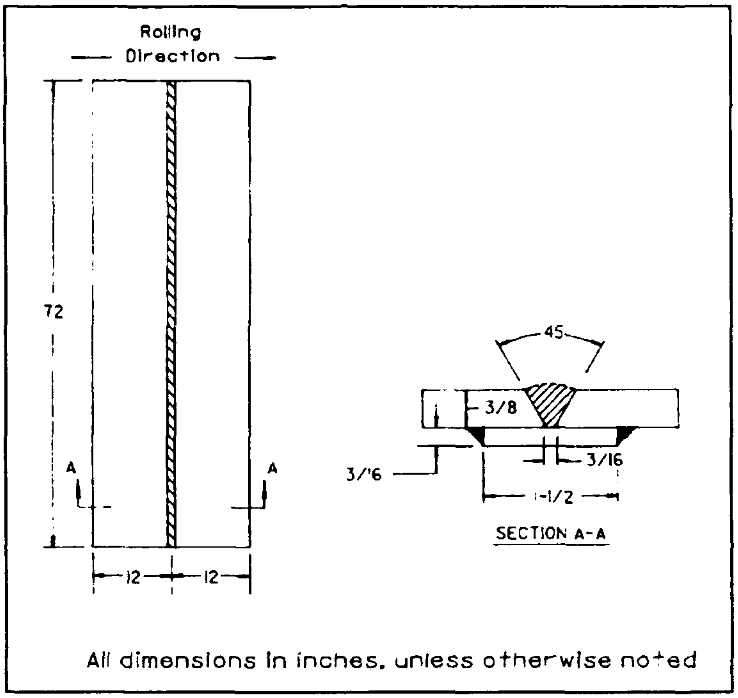


Figure 3.4 Wet Welded Fatigue Test Plate WW-PL1 and WW-PL2

4) After removal of the backing bar and backgrinding of the weld root, the plate was repositioned in the diving tank. The weld was then completed from the backside in the wet.
5) After completion of the weld, the plate was removed from the tank and VT and MT were performed over 100% of the weld length. The plate successfully met the VT and MT acceptance criteria. As with the air welded plate AW-PL1, the weld reenforcement was not removed.
6) The completed weldment was again subjected to RT by Global X-Ray. It was found that, while the weldment met ANSI/AWS D3.6 Type B criteria, it did not meet the specified acceptance criteria of NAVSHIPS 0900-LP-003-9000 (Class 3). This document allows 5/8" accumulated slag length over a 6" weld length for 3/8" thick material. RT on this weldment indicated a 1" accumulation of slag over a 2-1/4" length of weld, probably at the joint bevel between the root and hot pass. These type of defects could be detected (through RT or UT or, to a lesser degree, MT of each weld layer) and repaired in production, where high quality is required. A joint design facilitating a two pass root layer would also reduce the tendency for entrapment of

slag. For this task, it was decided that repair of the weldment was not necessary, as it would be possible to cut around the affected area when preparing the wet weld fatigue specimens. The location of the slag inclusion on the plate was clearly marked to ensure that it would not be included in any fatigue specimens.

7) After completion of all required NDE, the weldment was prepared for shipment to the machine shop for fabrication of the wet welded fatigue specimens.

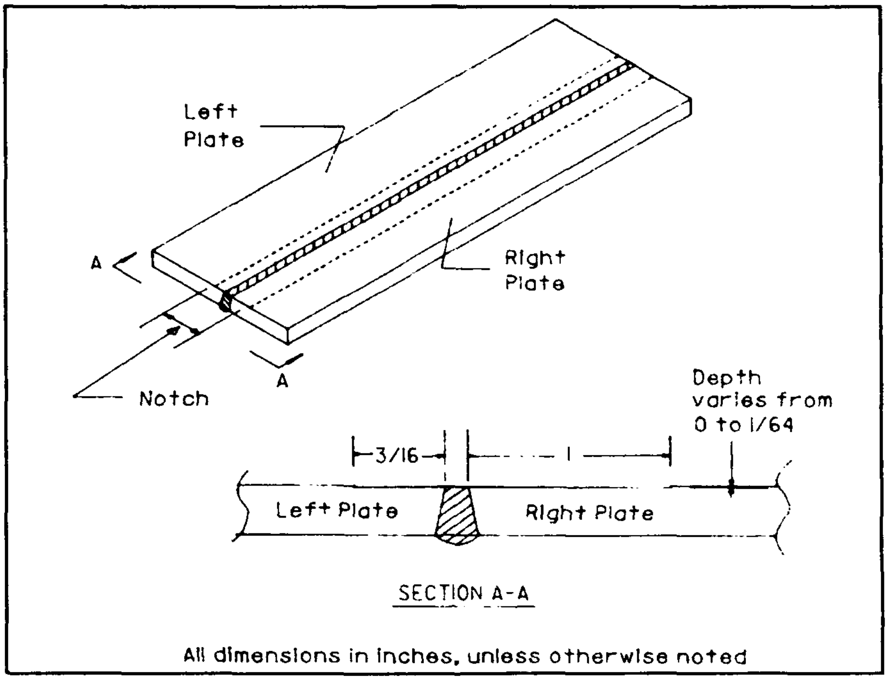


Figure 3.5 Wet Welded Fatigue Plate WW-PL1 After Removal of Backing Bar

3.2.4.7 Fabrication of Wet Welded Test Plate WW-PL2

The design of the wet welded fatigue specimen test plate (WW-PL2) was similar to the design of the wet welded fatigue test plate WW-PL1, shown in Figure 3.4. In fabricating weldment WW-PL2, the following steps were taken:

1) Two 72" x 12" x 3/8" plates were fit up with a 3/16" thick backing bar, as shown in Figure 3.4. Plate fit-up and tack welding of backing bar were performed in air.
2) The test assembly was lowered into the fresh water diving tank and positioned so that welding took place in the vertical position, at a depth of 30 FSW.
3) Welding was performed in the vertical down position using the wet welding procedure described previously.
4) Following welding, VT and MT were performed over 100% of the weld length. The plate successfully met the VT and MT acceptance criteria. As with the wet welded plate WW-PL1, the weld reinforcement was not removed.
5) RT was performed over 100% of the weld length, with the backing bar in place. As with plate WW-PL1, it was found that weldment WW-PL2 did not meet the specified acceptance criteria of Section 3.2.4.4. In this case, a slag inclusion 2-1/4" in length over a 4" length of weld was revealed. In a production setting, this defect would

normally be detectable and repairable. As it was possible to work around this defect in this program, however, repair of the weld defect was not performed.

6) As discussed in Section 2.5 of this report, previous fatigue studies of air welded specimens have shown that the presence of a backing bar causes a reduction in the fatigue life of welded structures [11]. Since it is not unusual to leave a backing bar in place in a wet welding production setting, an indication of the degree of degradation in the fatigue life of wet welded specimens due to the presence of a backing bar provides relevant and useful data. Accordingly, the 72" long wet welded plate WW-PL2 was cut to form two plates, 52" and 20" in length, as shown in Figure 3.6. The backing bar on the 52" long plate (designated plate WW-PL2A) was ground off, as with the specimens cut from plate WW-PL1. The 20" long plate (hereafter designated as plate WW-PL2B) was left with the backing bar in place, to be used in fabricating wet fatigue specimens with backing bar material.
7) Plate WW-PL2A was returned to a vertical position in the diving tank at a depth of 30 feet. The weld was then completed in the wet.
8) Plate WW-PL2A was removed from the tank and subjected to VT, MT, and RT. All acceptance criteria for MT and VT were met, and RT showed the 2-1/4" slag inclusion previously reported. As with plate WW-PL1, this slag inclusion was clearly marked and left in place, as it was possible to cut around it when preparing wet fatigue specimens.
9) After completion of all required NDE, plates WW-PL2A and WW-PL2B were shipped to the machine shop for fabrication of the wet welded fatigue specimens.

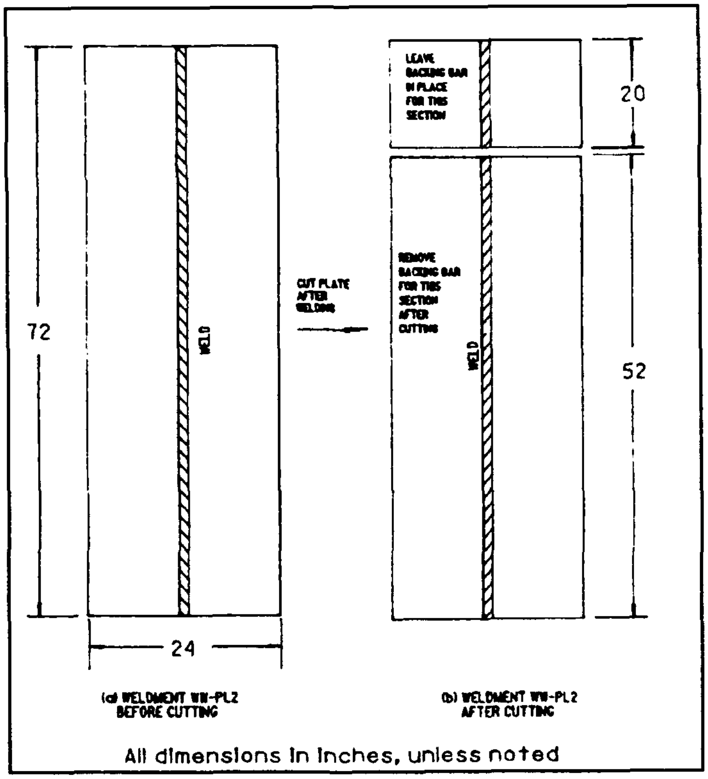


Figure 3.6 Wet Welded Fatigue Test Plate WW-PL2 After Cutting

3.2.5 Machining and Preparation of Fatigue Specimens

All welded plates were shipped to Tooling Specialists, Inc., of Latrobe, Pennsylvania for machining and preparation of fatigue specimens. Specimen design was in accordance with the specifications of ASTM E 466-82 [29], and typical fatigue specimen geometry is shown in Figure 3.7.

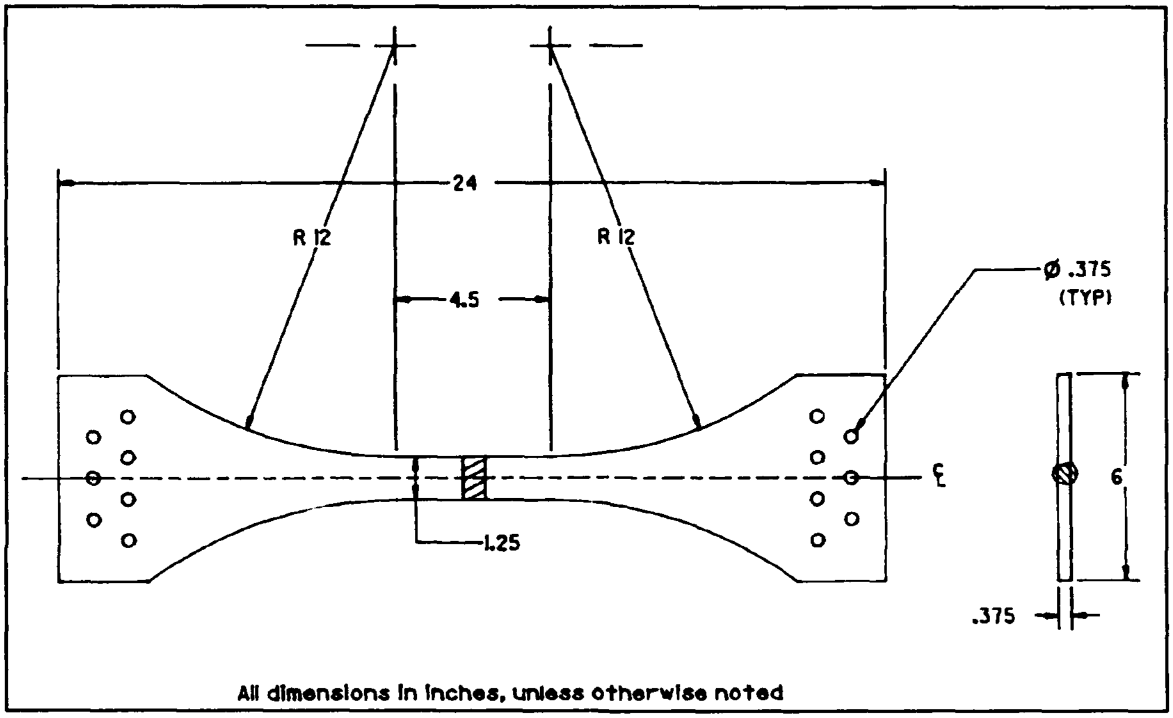


Figure 3.7 Typical Fatigue Specimen Design

3.2.5.1 Fatigue Specimen Preparation (Plates WW-PL1 and AW-PL1A)

Upon receipt of the welded test plates AW-PL1A and WW-PL1 by Tooling Specialists, Inc., two conditions were immediately apparent. The first, as discussed earlier, was the notch that had been cut into the wet welded plate WW-PL1 when the backing bar was removed. A condition such as this presents a potential problem in fatigue testing, as the notch edges act as stress raisers which will initiate fatigue cracking more readily than a smooth specimen. To eliminate this possibility, individual fatigue specimens were cut from the test plate, and then machining operations were performed on each individual fatigue specimen to remove the notch and eliminate the stress raiser. As seen in Figures 3.5 and 3.8(a), the fabricated weld was not centered in the notch. The first step in the machining operation was to remove additional base plate material on the "short" side of the notch in order to center the weld in the notch, as shown in Figure 3.8(b). The depth of the notch was not allowed to exceed its existing maximum depth of 1/64". Once the weld had been centered in the notch, the edges of the notch were "smoothed out" to provide a gentle transition in base plate thickness, as shown in Figure 3.8(c). The resulting fatigue specimens then varied in thickness from 24/64" (3/8") to 23/64" in the vicinity of the weld. As discussed earlier in this report, thickness of fatigue test specimens appears to be a second

order effect, and the reduction of specimen thickness should not invalidate these test results for comparison with specimens of different thicknesses.

The second condition, observed in both the air and wet welded test plates AW-PL1A and WW-PL1, was an approximate 3/8" bow in each plate, centered on the weld, in the transverse direction of the plate. The origin of this bow is somewhat of a mystery, as all plates were rigidly clamped during welding operations in order to prevent bowing due to weld shrinkage. In order to alleviate expected bowing after completion of welding and removal of the clamps, the weldments were actually bowed in the reverse direction 1/8" to 3/16", using clamps, after completion of each root pass. It is possible that the condition resulted during storage or transportation of the plates, but all attempts to determine the cause of the excessive bow proved fruitless.

To alleviate this bow in the weldments, each fatigue specimen cut from plates WW-PL1 AW-PL1A was straightened at room temperature in 3-point bending, with the load applied through flat steel bars along the specimen surfaces. Copper shims were placed on the bars to avoid damage to the specimen surfaces. After straightening, all specimens were examined with dye penetrant and showed no indications of cracks or porosity.

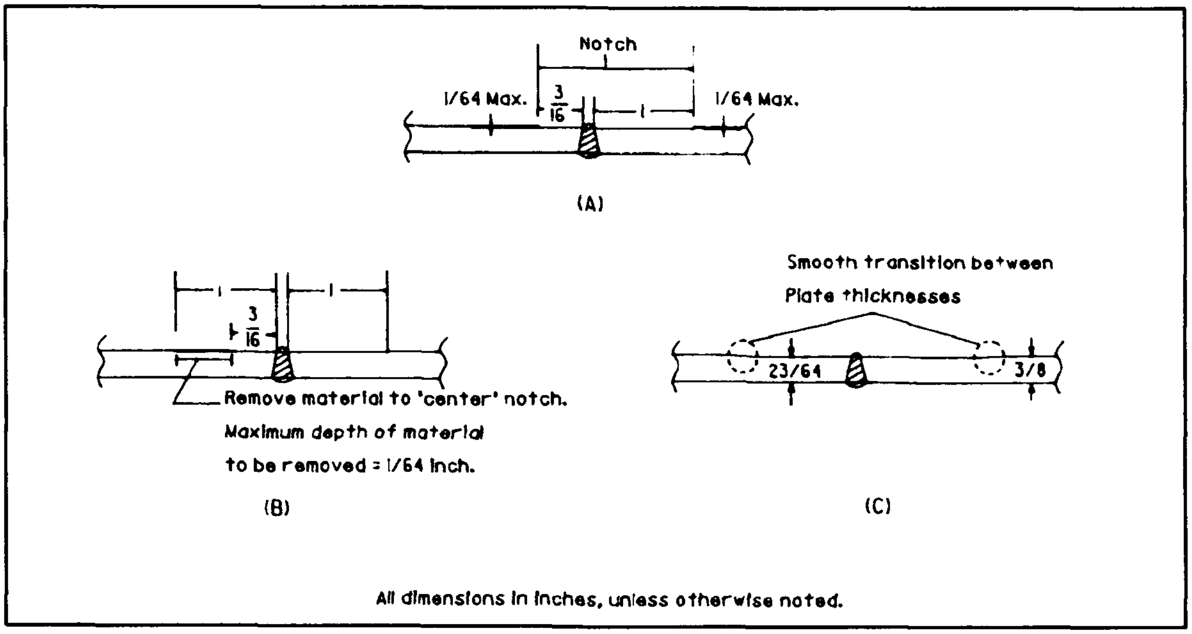


Figure 3.8 Removal of Notch in Fatigue Plate WW-PL1

Figure 3.9 depicts the cutting pattern used to prepare fatigue specimens from plates WW-PL1 and AW-PL1A. The location of each numbered specimen, showing its position on the welded test plates, is as depicted. Nine wet welded fatigue specimens were prepared from plate WW-PL1, and four air weld fatigue specimens were prepared from plate AW-PL1A. The wet weld fatigue specimens numbered WW4 and WW7 shown on the cutting diagram were not machined due to excessive undercut in the weld.

After cutting the fatigue specimens from the welded test plates as shown in Figure 3.9, the notch cut into each wet fatigue specimen was machined out, as explained in previous paragraphs. Each of the air and wet specimens was then bent carefully into a flat condition

using a three point press.

In order to preclude premature crack initiation along the edges of the specimens. the machining procedure given in Example XI of E 466-82 was used for edge preparation (this same procedure was used to machine the undercut side of the wet weldments so as not to introduce stress risers that could lead to crack initiation in the machined portion of the surface). All other surfaces of the specimen were left in the as-received condition.

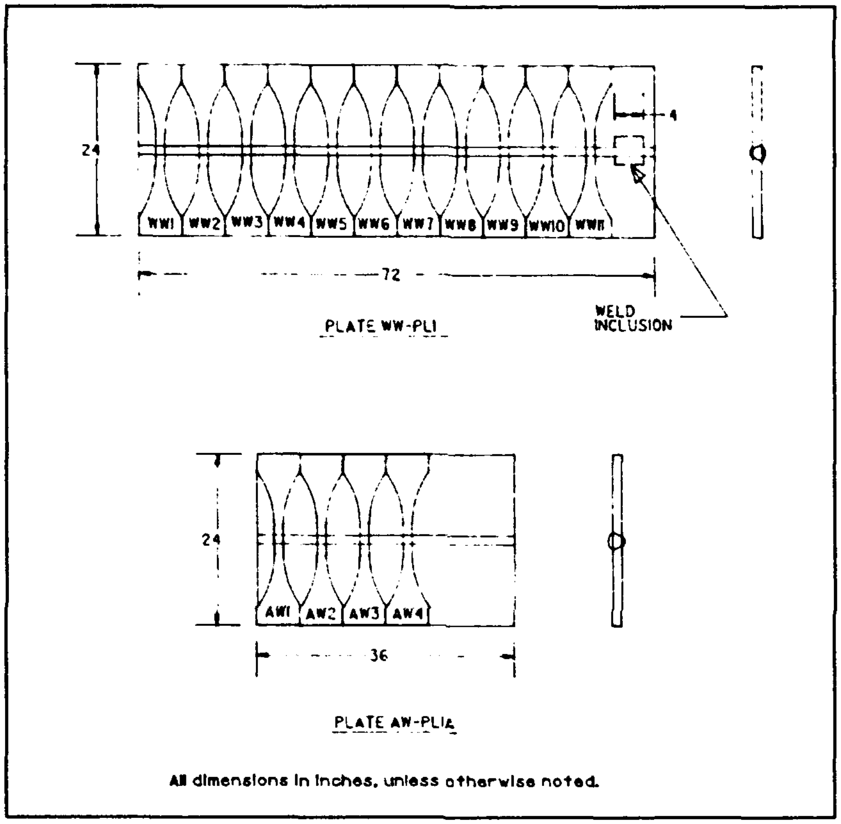


Figure 3.9 Cutting Pattern for Plates WW-PL1 and AW-PL1A

3.2.5.2 Fatigue Specimen Preparation (Plates WW-PL2A and WW-PL2B)

Figure 3.10 depicts the cutting pattern used to prepare wet welded fatigue specimens from plates WW-PL2A and WW-PL2B. The location of each numbered specimen, showing its position on the welded test plates, is as depicted. Six specimens were prepared from plate WW-PL2A (without backing bar), and three specimens were prepared from plate WW-PL2B (with backing bar).

No appreciable bow was observed in the wet welded test plates WW-PL2A and WW-PL2B, and the backing bar had been removed cleanly from plate WW-PL2A. Edge preparation of all specimens was performed in the same manner as for the WW-PL1 and AW-PL1A specimens.

3.2.6 Fatigue Testing of Welded Specimens

All fatigue testing was conducted by Material Engineering Associates (MEA) of Lanham, Maryland. All testing was conducted in air at room temperature, and was conducted in accordance with the requirements of ASTM E 466. Testing was conducted in a servohydraulic test machine under a sinusoidal wave form, at a stress ratio (R) of 0.1.

To assure axial alignment of the test machine and grips, as required by ASTM E 466, MEA first machined and loaded a rectangular demonstration plate having the dimensions of 6" x 3/8" x 24". Strain gages were placed on the edges of the demonstration plate and on the center of both surfaces of the plate at the w/2 location, where w is the width of the demonstration plate (6 inches). The demonstration plate was then cycled through a loading series, and strain gage measurements were recorded and checked to ensure that the test machine and grips were in alignment to within the tolerances specified in ASTM E 466. Once the alignment of the test machine and grips was satisfactorily set, fatigue testing of the wet and air welded specimens began. Strain gaging of selected specimens was performed during the testing program to ensure that the alignment of the testing apparatus remained within allowable tolerances.

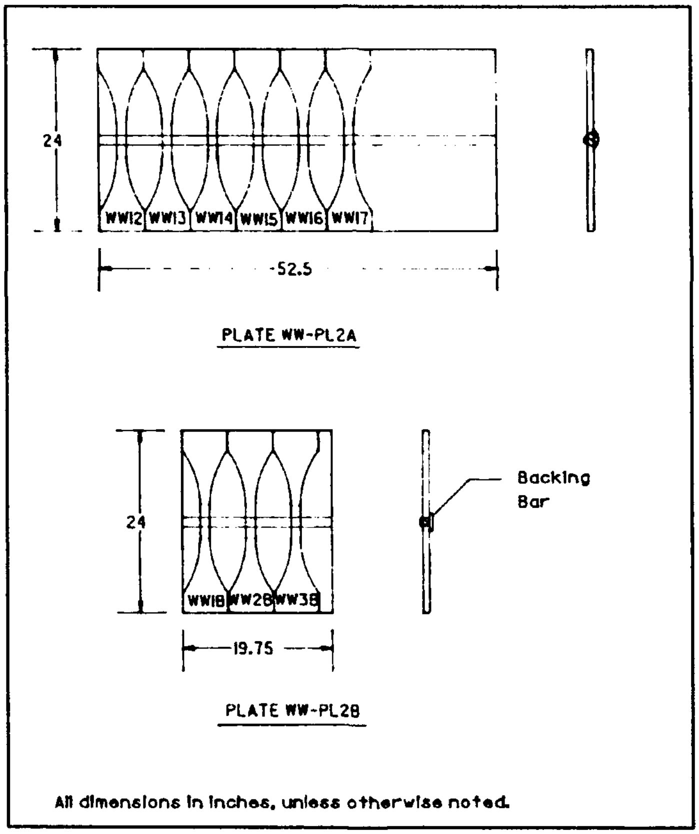


Figure 3.10 Cutting Pattern for Fatigue Test Plate WW-PL2

Loads were applied to all fatigue test specimens to produce the nominal stress levels (not considering the weld crown) shown in Table 3.2. Due to slight variations in specimen cross-sectional area (due to the machining necessary to remove the notch in the specimens

prepared from plate WW-PL1), the applied loads needed to produce identical stress levels varied from specimen to specimen.

Examining Table 3.2, it is seen that a total of 15 wet weld fatigue specimens (without backing bars) were tested at 5 different stress range levels. The criteria of ASTM E 739 [30] recommends that a minimum of 12 to 24 specimens be tested in order to generate design allowable or reliability data; the 15 specimens tested in this program are therefore adequate for this purpose. Using the methods of ASTM E 739, the percent replication for this test program is 73%, which qualifies as good replication for the generation of design allowables data (50% to 75% replication recommended).

Specimens were tested at the highest frequencies allowed on the test frame for each applied load level, ranging from 10 to 50 cycles per second. Testing for each specimen continued until complete separation of the specimen occurred, or until some agreed upon cyclic runout was achieved. The results of the testing program are presented in Section 4.0 of this report.

Table 3.2 Fatigue Testing Stress Levels

Weld Plate No.	Fatigue Specimen Number	Type	Max. Stress (psi)	Stress Range[1] (psi)
AW-PL1A	AW4	Air(w/o backing bar)	40000	36000
AW-PL1A	AW3	Air(w/o backing bar)	32000	28800
AW-PL1A	AW1	Air(w/o backing bar)	25000	22500
AW-PL1A	AW2[2]	Air(w/o backing bar)	25000	22500
WW-PL1	WW1	Wet(w/o backing bar)	40000	36000
WW-PL2A	WW12	Wet(w/o backing bar)	35000	31500
WW-PL2A	WW13	Wet(w/o backing bar)	35000	31500
WW-PL2A	WW14	Wet(w/o backing bar)	35000	31500
WW-PL1	WW10[2]	Wet(w/o backing bar)	30000	27000
WW-PL1	WW11	Wet(w/o backing bar)	30000	27000
WW-PL2A	WW15	Wet(w/o backing bar)	30000	27000
WW-PL2A	WW16	Wet(w/o backing bar)	30000	27000
WW-PL1	WW2[2]	Wet(w/o backing bar)	25000	22500
WW-PL1	WW3	Wet(w/o backing bar)	25000	22500
WW-PL1	WW5	Wet(w/o backing bar)	25000	22500
WW-PL2A	WW17	Wet(w/o backing bar)	25000	22500
WW-PL1	WW6	Wet(w/o backing bar)	20000	18000
WW-PL1	WW8	Wet(w/o backing bar)	20000	18000
WW-PL1	WW9	Wet(w/o backing bar)	20000	18000
WW-PL2B	WW1B	Wet(with backing bar)	25000	22500
WW-PL2B	WW2B	Wet(with backing bar)	25000	22500
WW-PL2B	WW3B	Wet(with backing bar)	25000	22500

[1] Stress Range = (1-R) x Max. Stress, where R = 0.1

[2] Specimen was strain gaged

3.3. DUCTILITY INVESTIGATION

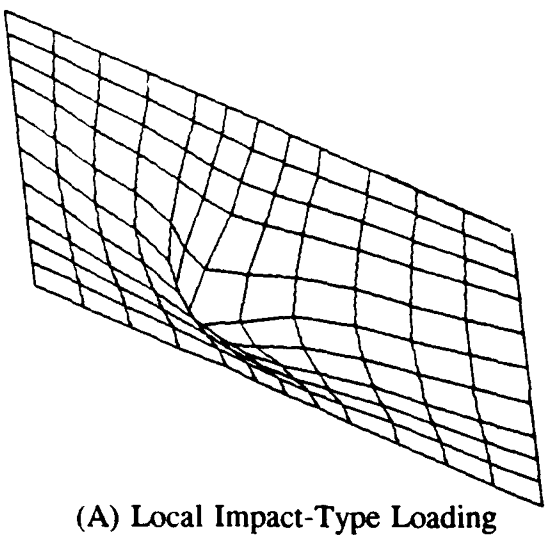
3.3.1 General

As reported earlier in this report, wet welds are characterized by high hardness and

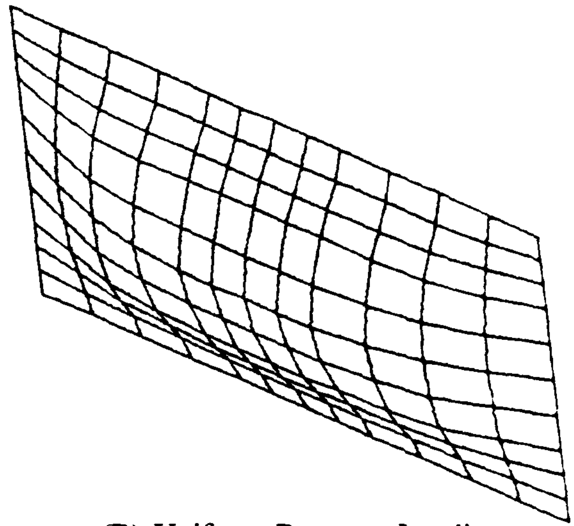
low ductility, when compared to surface air welds. Reported wet weld ductility values of 6% to 8% are below the ductility values required by various military and commercial specifications (ranging from 14% to 24%). In order to evaluate the significance of elongation values in this range when applying wet welding repair techniques to commercial shipping, a series of finite element structural analyses were conducted. In these analyses, typical ship plate panels were subjected to the following loading conditions:

- Localized, center panel impact-type loading
- Uniform pressure loading over the entire panel

Typical deformation patterns for a plate subjected to either a uniform pressure load or a localized load at the center of the panel are shown in Figure 3.11. Strain contours for the loaded plate panels were generated in order to determine if there were areas of the panels which would be structurally compromised by the use of wet welds.



(A) Local Impact-Type Loading



(B) Uniform Pressure Loading

Figure 3.11 Typical Plate Panel Deformation Shapes

For this study, the different plate thicknesses and panel aspect ratios which were addressed are summarized in Table 3.3. Each plate was assumed to be fully fixed along all edges, and large deformation, high strain finite element analyses using nonlinear material models were performed.

Table 3.3 Plate Aspect Ratios and Thicknesses Used in Ductility Study

Panel Size (inches)	Plate Thickness (inches)	
24 x 24 (Aspect Ratio = 1.0)	3/8	5/8
48 x 24 (Aspect Ratio = 2.0)	3/8	5/8

The finite element analyses were performed using the PC-based finite element program COSMOS/M. This program was shown in Reference 31 to be a highly accurate,

cost and time effective tool for the analysis of large deformation, high strain problems. The material nonlinearity for each element of the models was represented through the use of a multi-linear stress-strain curve, representative of an ABS Grade B steel, input to COSMOS/M.

In setting up a finite element model for a nonlinear analysis on COSMOS/M, the user may select from a number of options related to such things as the solution method to be used, the integration scheme, and the element representation [32]. The most effective combination of options for the problem at hand have been determined from previous experience with the COSMOS/M program in nonlinear analysis problems [31]. The design options chosen for the analyses are as follows:

- Type of Element: Nonlinear 20-node isoparametric solid, using 3x3x3 integration order
- Problem Formulation: Large displacement, Updated Lagrangian formulation
- Material Type: Von-Mises elasto-plastic model, utilizing a multi-linear stress-strain curve
- Solution Technique: Regular Newton-Raphson Method
- Integration Method: Newmark-Beta Method

3.3.2 Local Impact Loading

Commercial ship structure, while not subject to the blast load design criteria required on combatant ships, may still experience local impact loadings due to collisions with tugboats, piers, floating debris, and the like. To evaluate the effects of local impact on panel deformation characteristics and local strain levels, finite element analyses simulating the impact of a ship underway at approximately 8 knots striking a 500 pound mass were conducted. Such an impact would impart approximately 16,000 inch-pounds of energy to the ship plate panel at the point of impact. Similar impact energy scenarios have been used by the U.S. Navy to evaluate the impact performance of new hull structural materials.

The COSMOS/M models used for these local impact analyses are shown in Figures 3.12 and 3.13 (for aspect ratios of 2.0 and 1.0, respectively). To model the local impact loading on the plate panels, a 500 pound mass element was placed at the center of each plate panel (Node number 98). The mass was placed at a single point on the model, instead of spreading its effects over some cross-sectional area, as this would represent a more severe loading condition. This mass was then given an initial velocity equal to approximately 8 knots, and a nonlinear dynamic analysis was performed to determine the time at which maximum displacement of the center point of the panel occurred. The displacement and strain contours over the plate panel at that time were then plotted to determine whether strains in the plate panel model exceeded 6% total strain.

Two additional loading cases were also analyzed to check the strain levels induced by impact loads. In each case, the panel with the higher aspect ratio (2.0) and the lower thickness (3/8") was used. In the first case, there was some question as to whether impact with a larger mass, at a lower velocity (where the total impact energy was still equal to 16,000 in-lbs) would yield significantly different results. Therefore, the velocity necessary to create 16,000 in-lb of impact energy with a 50,000 pound impactor was calculated. This case was then analyzed. In the second case, a surface ship was assumed to be underway at a maximum operational speed of 35 knots when it impacts a 500 pound mass floating in the water. The deflection and strain levels imposed on the plate panel for this case were then determined.

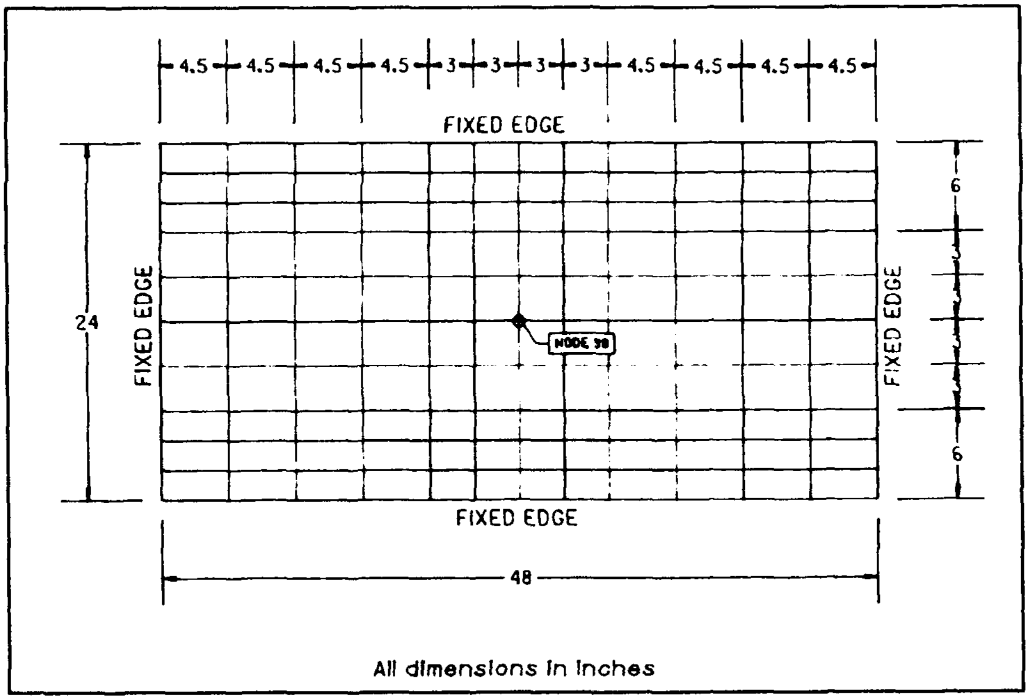


Figure 3.12 COSMOS/M Impact Load Model, a/b = 2.0

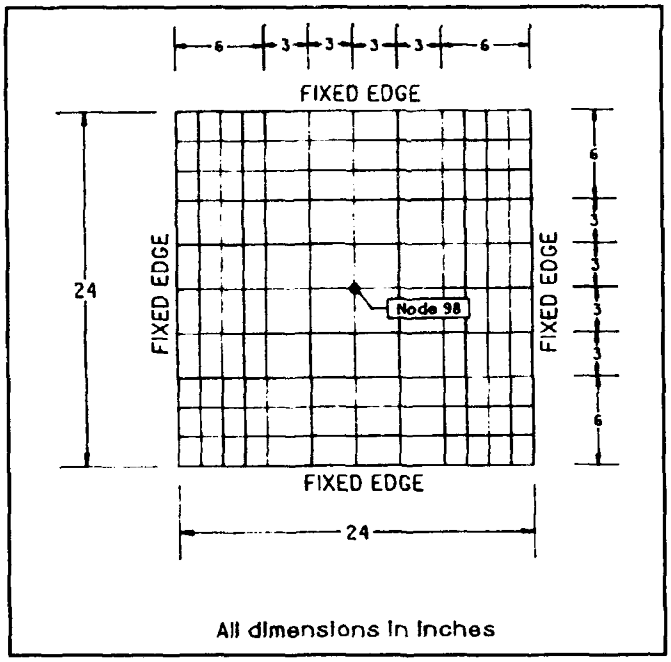


Figure 3.13 COSMOS/M Impact Load Model, a/b = 1.0

The parameters for each of the impact cases examined in this study are summarized in Table 3.4.

Table 3.4 Impact Study Panel Parameters

Case	Panel Aspect Ratio	Panel Dimensions	Panel Thickness (inches)	Impactor Weight (pounds)	Impact Energy (in-lbs)	Relative Impact Velocity (knots)
1	2.0	48" x 24"	3/8"	500	16000	8
2	2.0	48" x 24"	5/8"	500	16000	8
3	2.0	48" x 24"	3/8"	50000	16000	0.8
4	2.0	48" x 24"	3/8"	500	325111	35
5	1.0	24" x 24"	3/8"	500	16000	8
6	1.0	24" x 24"	5/8"	500	16000	8

3.3.3 Normal Pressure Loading

A typical 48" x 24" ship plate bounded by frames and longitudinal stiffeners, with a 12" by 12" steel patch welded in its center, is shown in Figure 3.14. This figure indicates the region of the plate actually modeled in the COSMOS/M analyses, using symmetry conditions. The COSMOS/M finite element model shown in Figure 3.15 is a model of this region. The mesh used to model the 24" x 24" plates, with a 12" x 12" welded patch (Figure 3.16), was constructed in a similar manner.

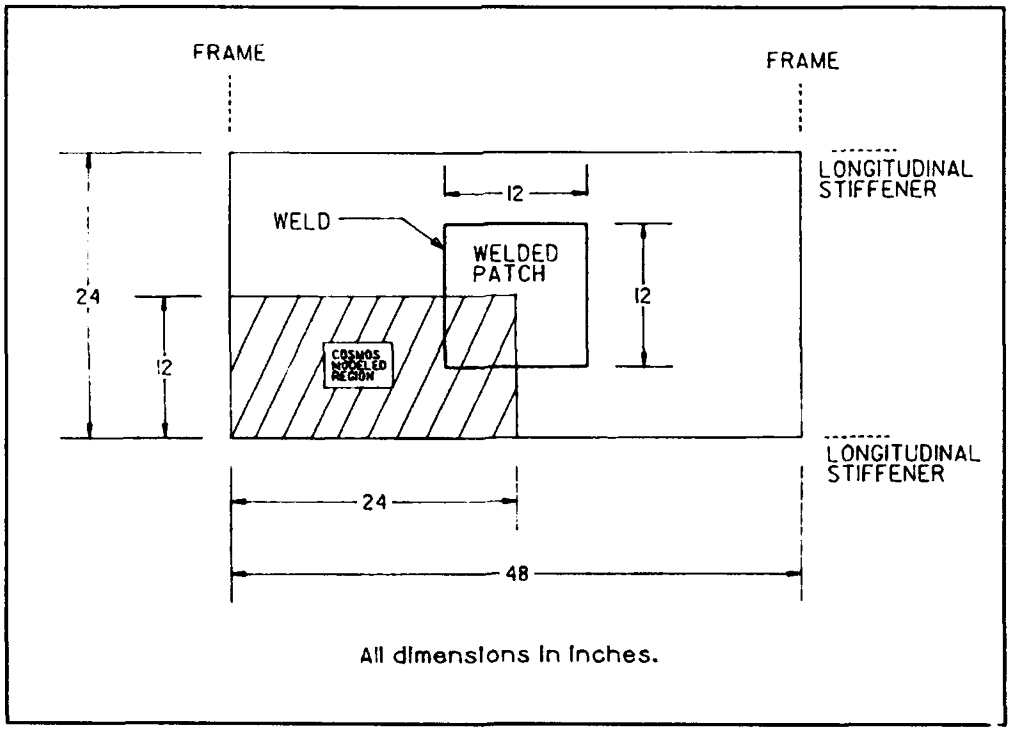


Figure 3.14 Typical Ship Plate Panel, Showing Region Modeled for Pressure Load A alysis

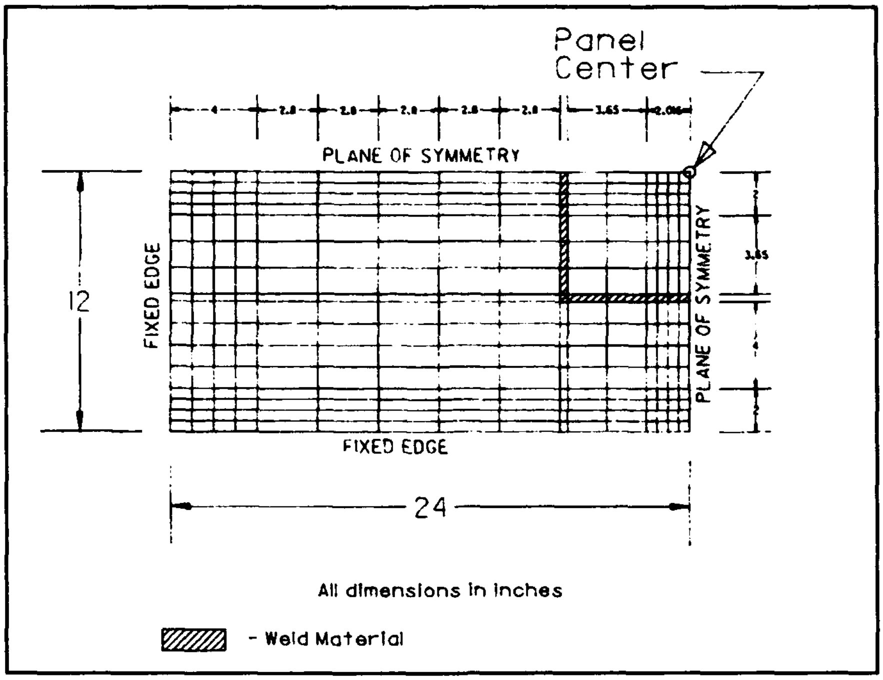


Figure 3.15 COSMOS/M Pressure Load Model, a/b =2.0

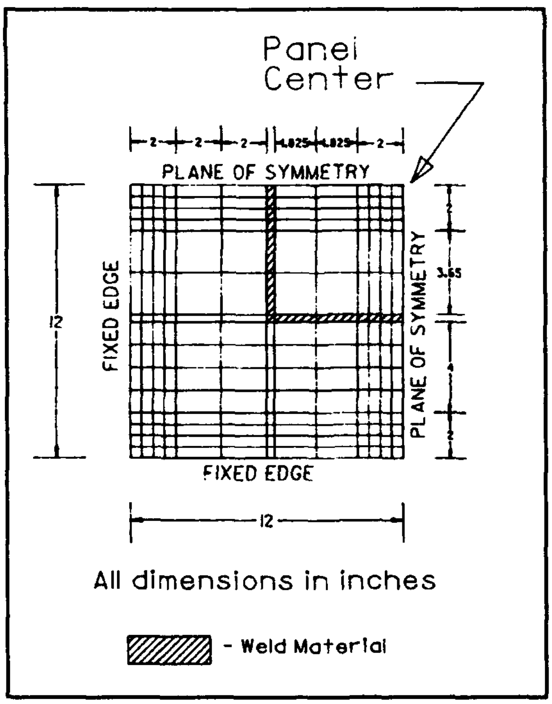


Figure 3.16 COSMOS/M Pressure Load Model, a/b =1.0

Each of the finite element models shown in Figures 3.15 and 3.16 was subjected to a uniform normal pressure load over its entire surface. The loads were input through the use of a linearly increasing load-time curve, shown in Figure 3.17. Output results were requested at time increments of every 0.005 seconds (increments of 50 psi per step). The analysis of each plate continued until strains of at least 6% were observed in any portion of the model. The results were then examined to determine the time step and resulting panel deflection at which the 6% strain levels were induced.

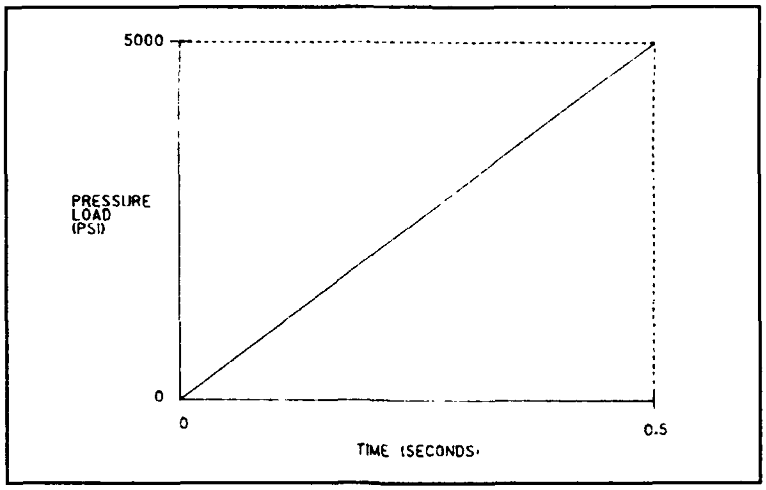


Figure 3.17 Load-Time Curve Used in COSMOS/M Pressure Load Analyses

SECTION 4.0
RESULTS AND DISCUSSION

4.1 FATIGUE TESTING

Fatigue test results for the specimens tested are shown in Table 4.1.

Table 4.1 Fatigue Testing Results

Weld Plate No.	Fatigue Specimen Number	Type	Max. Stress (psi)	Stress Range (psi)	Number of Cycles (10^6)	Result
AW-PL1A	AW4	Air(w/o backing bar)	40000	36000	0.33	break
AW-PL1A	AW3	Air(w/o backing bar)	32000	28800	5.96	runout
AW-PL1A	AW1	Air(w/o backing bar)	25000	22500	4.30	runout
AW-PL1A	AW2	Air(w/o backing bar)	25000	22500	1.98	break
WW-PL1	WW1	Wet(w/o backing bar)	40000	36000	0.24	break
WW-PL2A	WW12	Wet(w/o backing bar)	35000	31500	0.97	break
WW-PL2A	WW13	Wet(w/o backing bar)	35000	31500	0.99	break
WW-PL2A	WW14	Wet(w/o backing bar)	35000	31500	2.09	break
WW-PL1	WW10[2]	Wet(w/o backing bar)	30000	27000	1.35	break
WW-PL1	WW11	Wet(w/o backing bar)	30000	27000	7.00	runout
WW-PL2A	WW15	Wet(w/o backing bar)	30000	27000	0.47	break
WW-PL2A	WW16	Wet(w/o backing bar)	30000	27000	0.45	break
WW-PL1	WW2[2]	Wet(w/o backing bar)	25000	22500	6.95	runout
WW-PL1	WW3	Wet(w/o backing bar)	25000	22500	1.83	break
WW-PL1	WW5	Wet(w/o backing bar)	25000	22500	3.43	break
WW-PL2A	WW17	Wet(w/o backing bar)	25000	22500	0.91	break
WW-PL1	WW6	Wet(w/o backing bar)	20000	18000	5.00	runout
WW-PL1	WW8	Wet(w/o backing bar)	20000	18000	10.0	runout
WW-PL1	WW9	Wet(w/o backing bar)	20000	18000	10.0	runout
WW-PL2B	WW1B	Wet(with backing bar)	25000	22500	0.78	break
WW-PL2B	WW2B	Wet(with backing bar)	25000	22500	1.77	break
WW-PL2B	WW3B	Wet(with backing bar)	25000	22500	1.23	break

The fatigue test results for the air-welded specimens tested in this program are plotted against the baseline air S-N curve in Figure 4.1. The air-welded fatigue specimens

tested in this program were tested in order to ensure that the baseline air curve could be used with confidence for comparison purposes. If the air-welded fatigue specimens tested in this program had fatigue characteristics which varied significantly from the baseline curve, then there would have been no point in using the curve for comparison with the wet fatigue data.

As indicated from Figure 4.1, the air-welded specimens tested in this study have fatigue characteristics that are consistent with the baseline air S-N curve (the fatigue results are above the 95% lower confidence limit for the baseline air curve). Therefore, differences between the fatigue characteristics of the wet weld specimens tested in this program and the baseline air S-N curve are assumed to be due to the differences in fatigue properties, and not differences in the testing procedure.

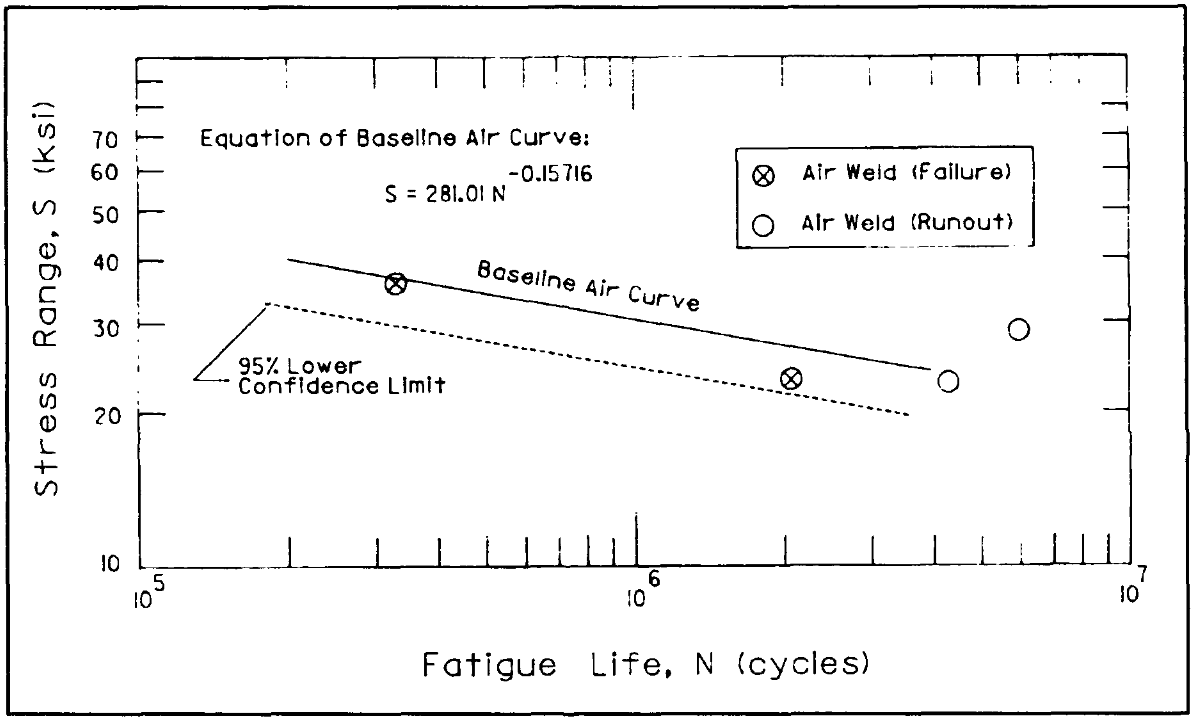


Figure 4.1 Air Welded Fatigue Testing Results vs. Baseline S-N Curve

The fatigue test results for the wet welded specimens (without backing bar) tested in this program are plotted in Figure 4.2. The data reduction methods of References 18 and 30 were used to generate the linear regression curve fit and 95% lower confidence limit shown in this figure. Using these methods, the equation of the linear regression best-fit curve for the wet weld fatigue specimens (without backing bar) was determined to be :

$$S = 600.4722 \times N^{-0.2235}$$

The correlation coefficient (r) for this curve, which reflects the adequacy of the fit of the curve to the observed data, was calculated to be 0.9295, indicating a tight "fit" for the wet weld fatigue data. The standard error of estimate (measure of the distribution of data about the best-fit fatigue curve) was calculated to be 0.136 for the wet weld fatigue curve shown in Figure 4.2. These values of the correlation coefficient and the error of estimate for the wet weld fatigue data indicate that the curve fit shown in Figure 4.2 is statistically sound.

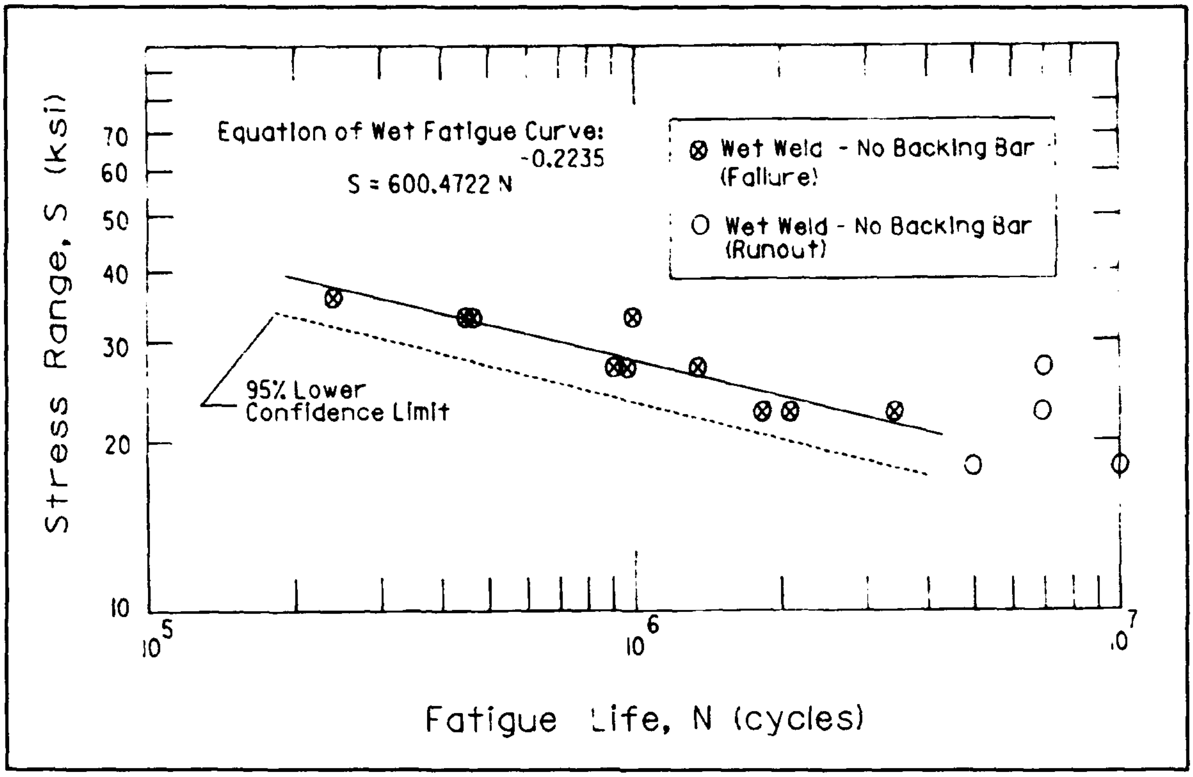


Figure 4.2 Wet Welded Fatigue Testing Results

For comparison purposes, the fatigue data points for the wet specimens (without backing bar) are plotted against the baseline air curve in Figure 4.3. From this figure, it is seen that almost all of the wet weld failures occurred at points above the 95% lower confidence limit for the baseline air curve. This indicates that, statistically, the wet transverse butt welds fabricated and tested in this study have fatigue lives which are not different and are comparable to the surface air welds represented by the baseline air curve.

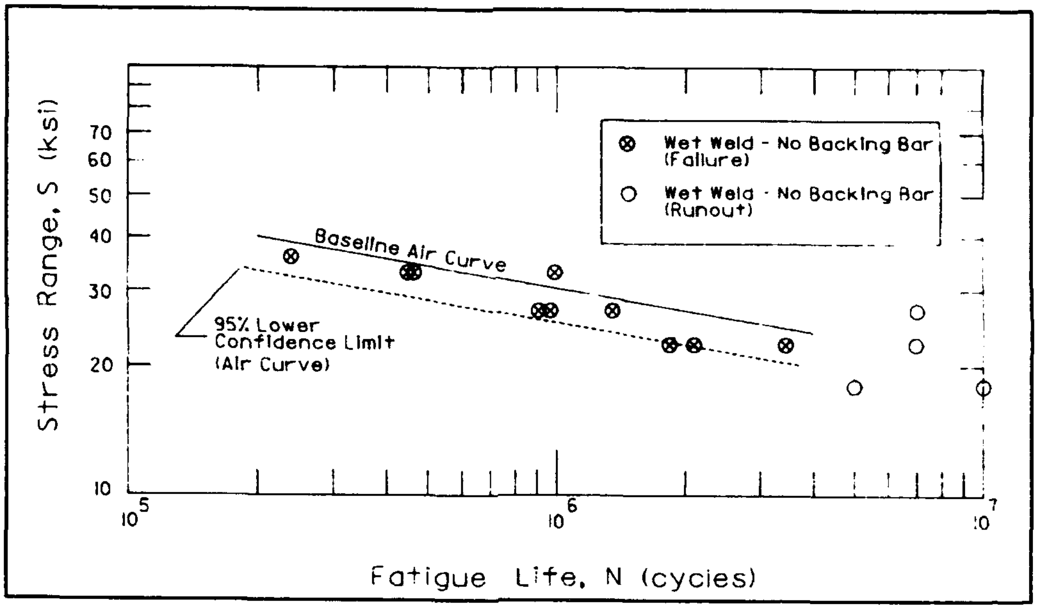


Figure 4.3 Wet Welded Fatigue Testing Results vs. Baseline S-N Curve

Table 4.2 summarizes the fatigue data results for the wet weld specimens tested at a stress range value of 22.5 ksi, with and without backing bars. This table gives the mean value, the standard deviation, the t-distribution, and the 95% confidence interval for each set of data: the first set of data containing the fatigue results for specimens WW3, WW5, and WW17 (without backing bar), and the second set of data containing the fatigue results for specimens WW1B, WW2B, and WW3B (with backing bar). The data summarized in Table 4.2 is depicted graphically in Figure 4.4.

From the results presented in Table 4.2 and Figure 4.4, it is noted that there is a significant difference in the mean value of fatigue life (cycles to failure) between the two sets of data (1.261×10^6 for the specimens with a backing bar vs. 2.449×10^6 cycles to failure for the specimens without a backing bar). However, due to the limited number tests and the nature of the results, a general statement cannot be made with 95% confidence that the fatigue life of wet welds with backing bars will be different from the fatigue life of wet welds without backing bars. Additional testing would be required in order to make a valid statistical statement concerning the effect of a backing bar on the fatigue life of wet transverse butt welds subjected to axial loading.

Table 4.2 Statistical Results for Wet Fatigue Specimens With and Without Backing Bars at 22.5 Ksi

Sample Data Set	Sample Mean (cycles)	Sample Standard Deviation (cycles)	t(0.975;2)	Confidence Interval
Wet Welds With Backing Bar	1.261×10^6	0.5×10^6	4.303	(18,898; 2,503,237)
Wet Welds Without Backing Bar	2.449×10^6	0.858×10^6	4.303	(316,313; 4,583,198)

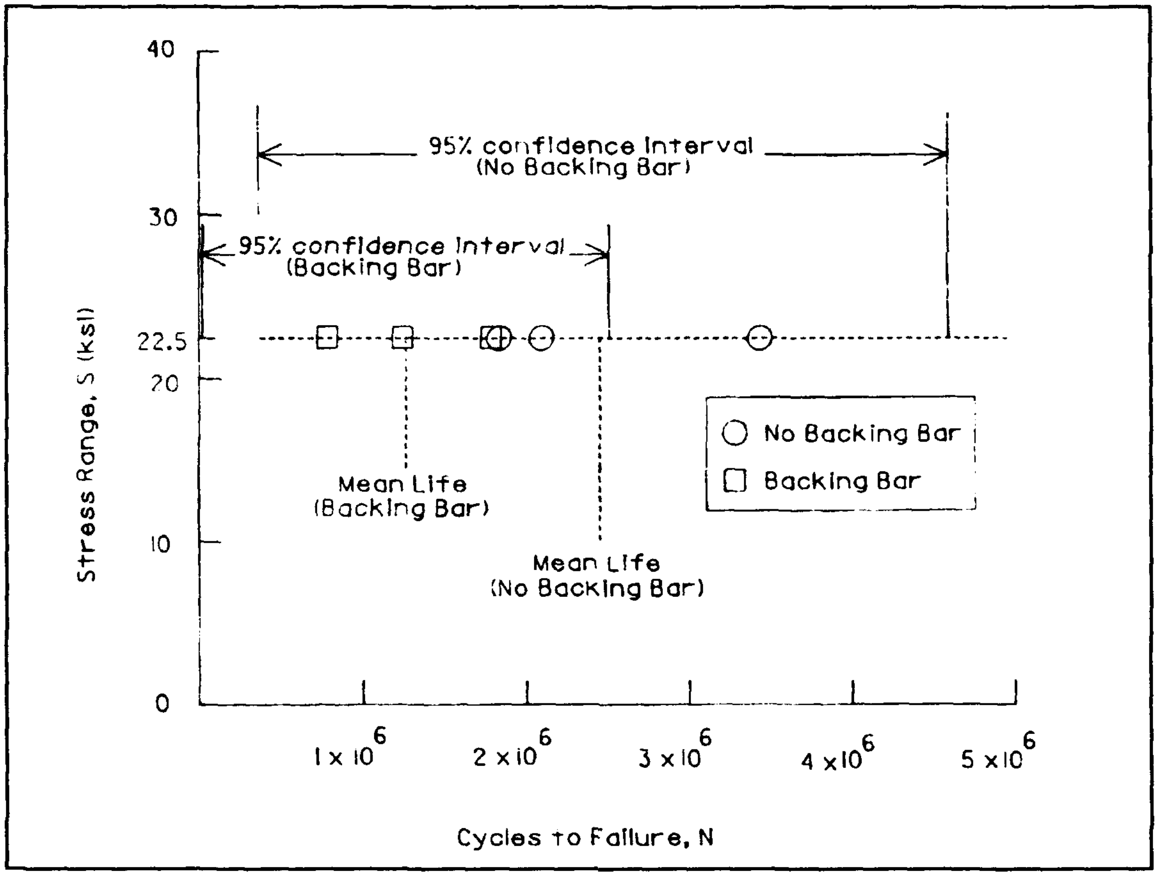


Figure 4.4 Wet Weld Fatigue Test Data (Backing Bar vs. No Backing Bar)

Sketches showing the failure locations for each failed specimen are shown in Figures 4.5, 4.6, and 4.7. None of the failed specimens gave any indication that failure was due to an inherent weakness or defect characteristic of a wet weld. All specimens experienced crack initiation in an region of abrupt change in cross-sectional area. Wet weld specimens WW1, WW3, WW12, WW13, WW15, WW16, and WW17, and air weld specimens AW2 and AW4, all showed indications of crack initiation at the weld toe; wet weld specimens WW5,WW10, and WW14 showed indications of crack initiation at a point in the weld material where one weld pass overlapped another (as shown in Figure 4.5), creating a "toe-like" point in the weld.

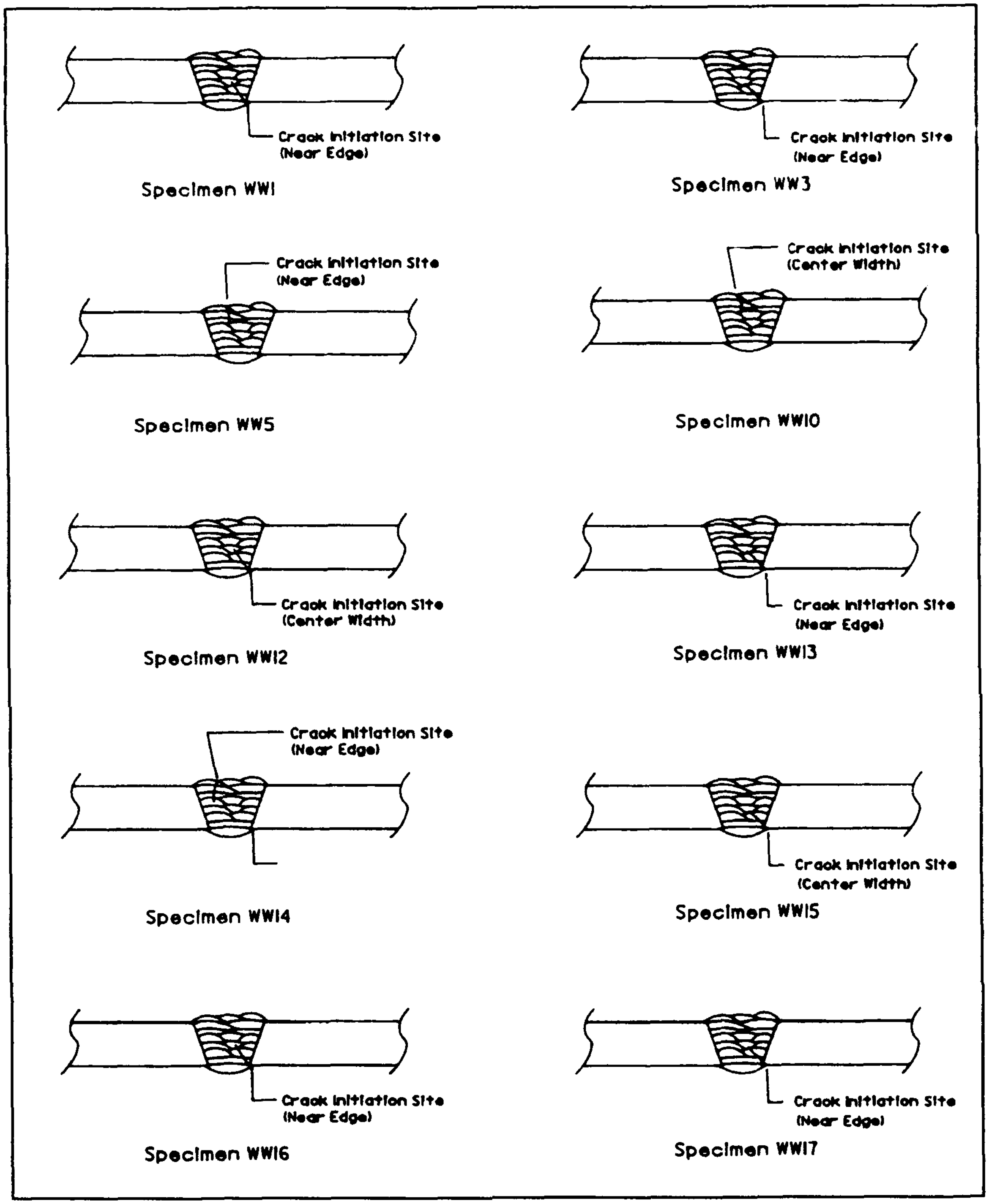


Figure 4.5 Failure Locations of Wet Weld Specimens (Without Backing Bars)

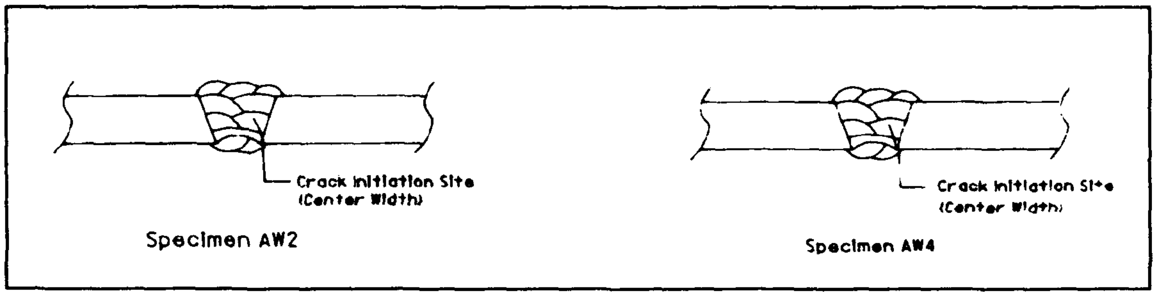


Figure 4.6 Failure Locations of Air Weld Specimens

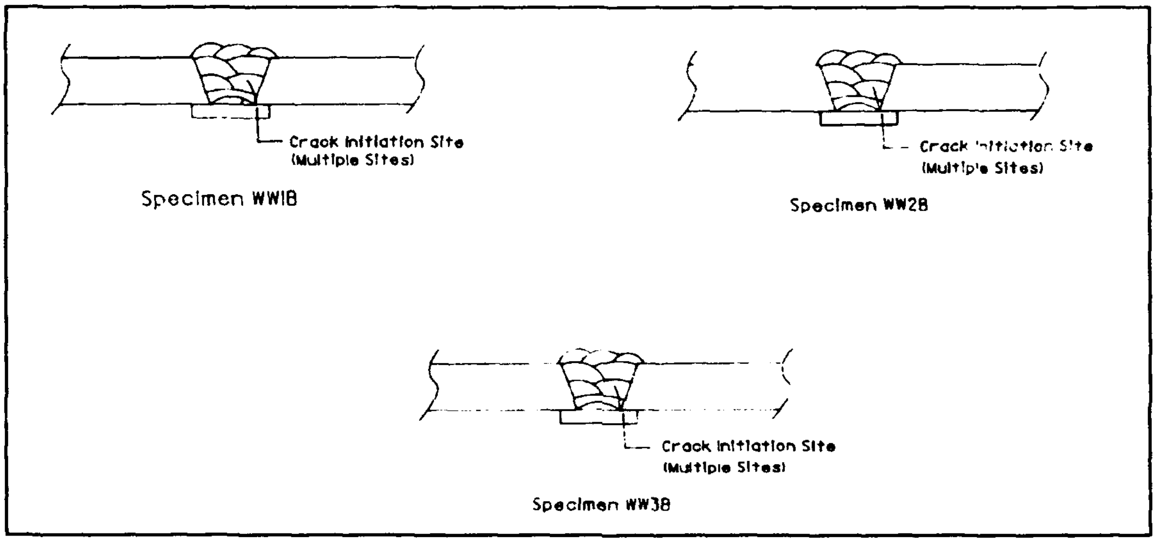


Figure 4.7 Failure Locations of Wet Weld Specimens (with Backing Bar)

It must be noted that the wet fatigue test results of this study were generated for a joint design fabricated using a specific welding process and procedure, and subjected to constant amplitude axial loading. As discussed earlier in this report, the fatigue characteristics of welded structural details are governed by factors such as the geometry of the detail, the materials used, the type of loading, etc., and are not generally transferrable to different structural details.

Additionally, the results of this fatigue testing program may not be applicable to wet welds fabricated using a different welding procedure (which may involve the use of a different welding process, electrode type, etc.). Testing specimens fabricated using different welding procedures is the only way to ensure that accurate fatigue performance data for those particular procedures is available.

This testing program has demonstrated that wet welding does not inherently produce welds with fatigue properties which are inferior to those exhibited by similar surface air welds. When properly applied and executed, a wet welding procedure can be used to fabricate weldments with fatigue properties comparable to surface air welds.

4.2 DUCTILITY INVESTIGATION

4.2.1 Local Impact Loading

Figures 4.8 and 4.9 illustrate the areas of maximum displacement and maximum strain resulting from the impact load finite element analyses performed in this study. These figures represent the results from Case 4 (48" x 24" x 3/8" panel subjected to 35 knot impact with a 500 pound mass) and Case 5 (24" x 24" x 3/8" panel subjected to 8 knot impact with a 500 pound mass), respectively, and are typical of the results obtained for the other cases. The maximum strain and displacement values calculated for each case are summarized in Table 4.3.

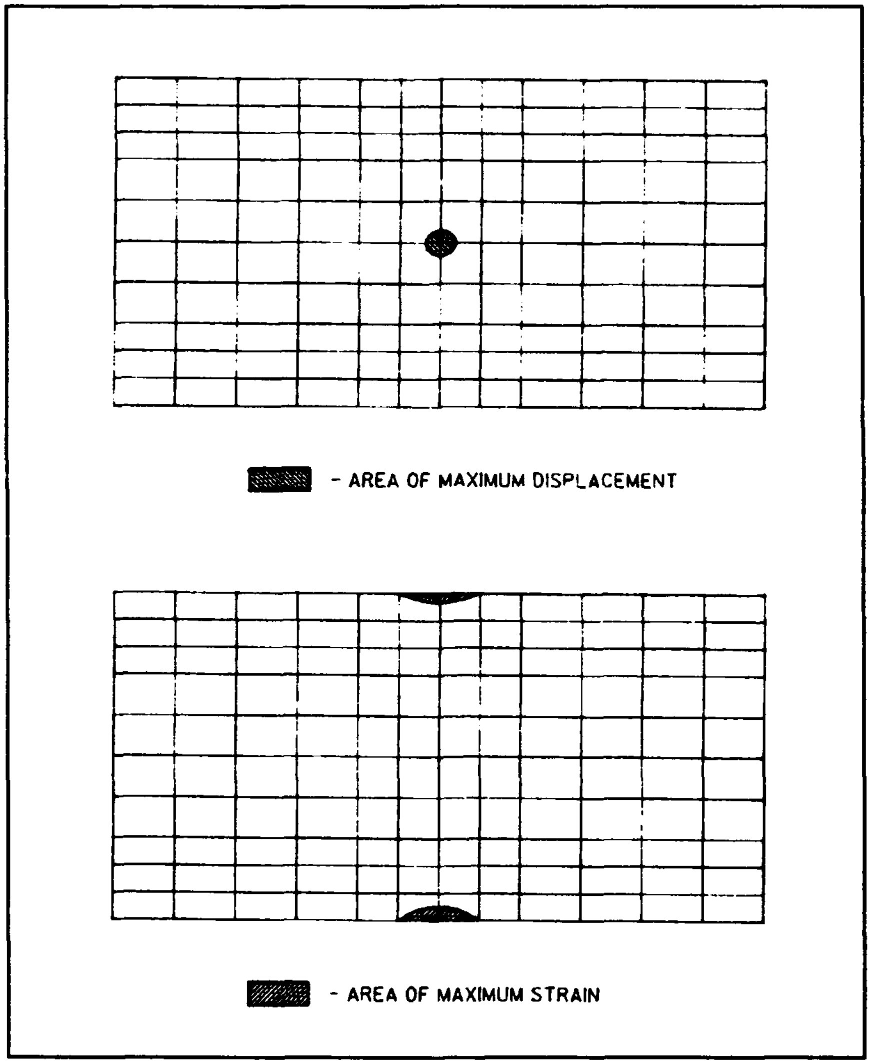


Figure 4.8 Location of Maximum Displacement and Strain for Case 4 Impact Loading (a/b = 2.0, t= 3/8")

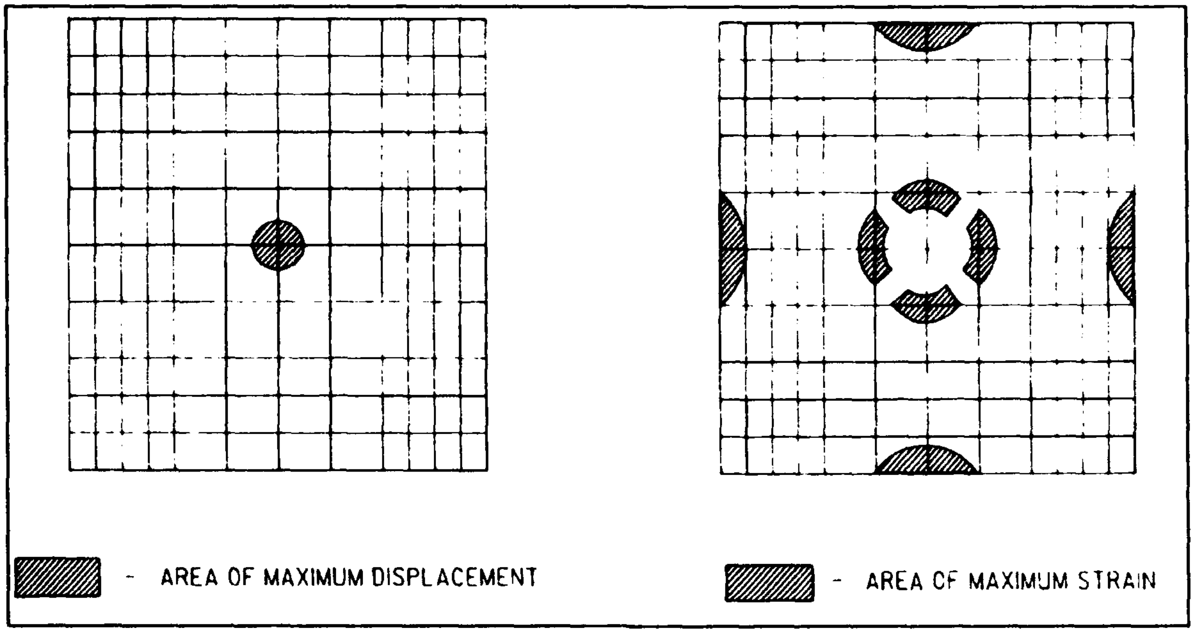


Figure 4.9 Location of Maximum Displacement and Strain
for Case 5 Impact Loading (a/b = 1.0, t= 3/8")

Table 4.3 Local Impact Study Results

Case	a/b	Panel Dimensions	Panel Thickness (inches)	Impactor Weight (pounds)	Relative Impact Velocity (knots)	Maximum Center Panel Displacement (inches)	Maximum Total Strain (%)
1	2.0	48" x 24"	3/8"	500	8	0.82	0.5
2	2.0	48" x 24"	5/8"	500	8	0.46	0.3
3	2.0	48" x 24"	3/8"	50000	0.8	0.83	0.5
4	2.0	48" x 24"	3/8"	500	35	2.95	3.2
5	1.0	24" x 24"	3/8"	500	8	0.75	0.4
6	1.0	24" x 24"	5/8"	500	8	0.41	0.3

Of the six cases examined, the highest strain levels, as expected, occurred for the case of a ship underway at 35 knots striking a 500 pound mass. The maximum strain values for this case, as shown in Table 4.3, are on the order of 3.2 %. Since it has been shown that wet welds are capable of achieving ductility levels of 6% to 8%, a local impact of the type analyzed herein should not cause failure of a wet weld placed in the plate.

4.2.2 Normal Pressure Loading

Figures 4.10 and 4.11 indicate the areas of maximum displacement and maximum strain resulting from the normal pressure loading finite element analyses performed in this study. These figures represent the results from Case 1 (48" x 24" x 3/8" panel) and Case 3

(24" x 24" x 3/8" panel), and are typical of the results seen for the other cases. Each of the figures represents a "snapshot" of the strain and displacement taken at the time step at which a strain of approximately 6% is first achieved. These values are summarized in Table 4.4. The center panel deflections at which 6% strain levels are first observed are typical of panel deflections observed in ship surveys of commercial ships [31]. As can be seen from Figures 4.10 and 4.11, the strain induced in the plates by the linearly increasing pressure loads applied in this study first reaches 6% at locations within approximately 4 inches from the edge of the panel. These results are in agreement with results reported in finite element analyses performed in Reference 31, which indicated a rapid build-up of strain near the fixed boundaries of loaded plate panels.

Table 4.4 Normal Pressure Load Study Results

Case	Panel Dimensions	Maximum Center Panel Displacement (inches)	Maximum Total Strain (%)	Time Step
1	48" x 24" x 3/8"	0.82	6.9	100
2	48" x 24" x 5/8"	0.72	6.4	250
3	24" x 24" x 3/8"	0.72	6.0	96
4	24" x 24" x 5/8"	0.81	6.4	160

Figures 4.10 and 4.11, and the results shown in Table 4.4, indicate areas in which the placement of low weld ductility welds may be a cause for concern. The results of these analyses indicate that placing a wet weld in a plate too near an area of fixity (such as a wet weld which passes over a frame or bulkhead) may compromise the integrity of the wet weld, due to the build-up of strain in these areas. It is recommended that wet welds be placed no closer than about 6" to an area of high restraint, lest the weld be overstrained. This approach is in agreement with the recommendations detailed in Reference 5, which stated that care should be exercised to ensure that a wet welded structure be designed in such a manner that some other portion of the structure, away from the weld, should first be plastically deformed. Although underwater wet welds would not be suitable for permanent repair applications in this case, they may be acceptable for temporary service, if the risk of sustaining significant plastic deformation and/or the consequence of weld failure are determined to be acceptable.

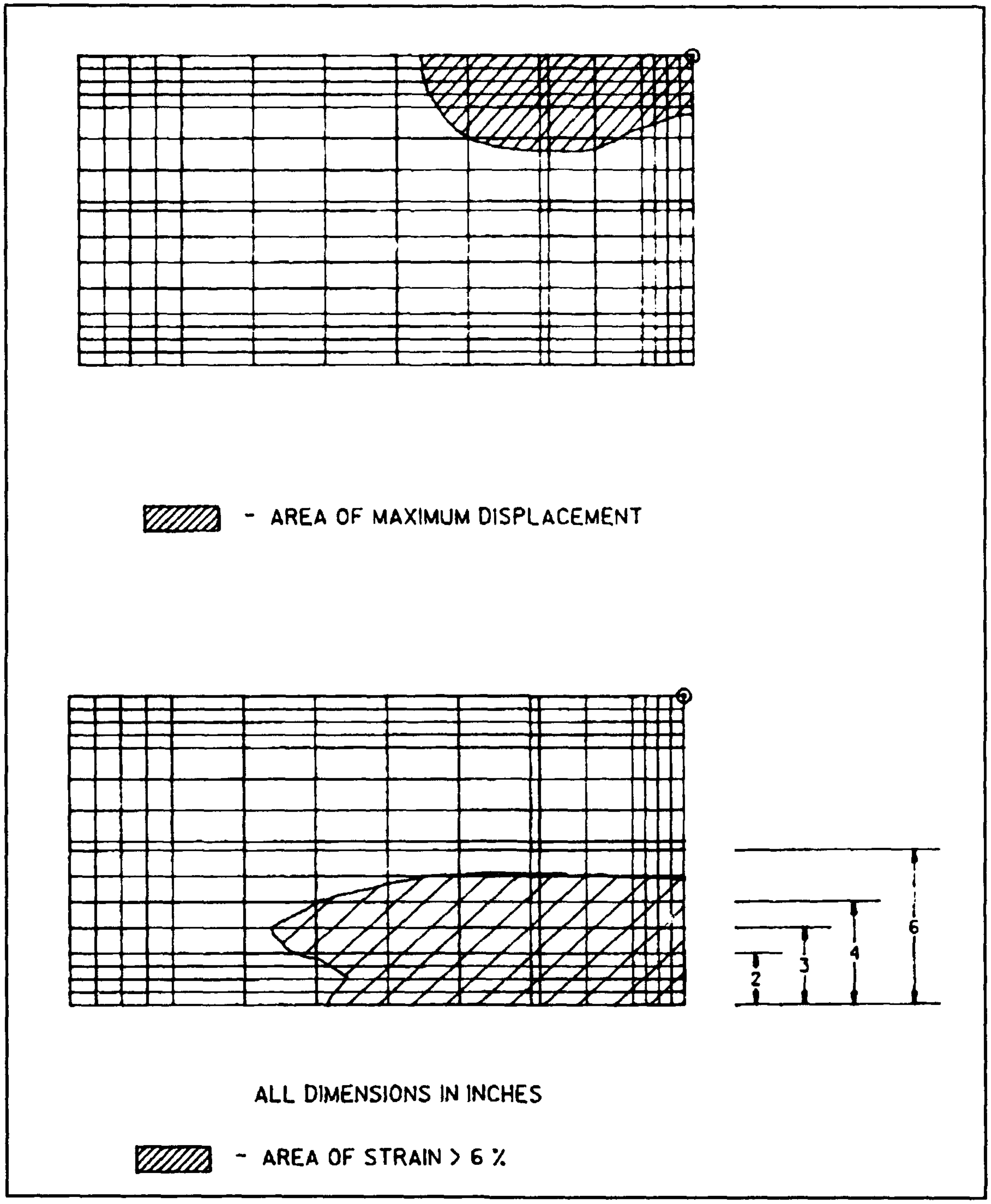


Figure 4.10 Location of Maximum Displacement and Strain for Case 1 Pressure Loading (a/b = 2.0, t= 3/8")

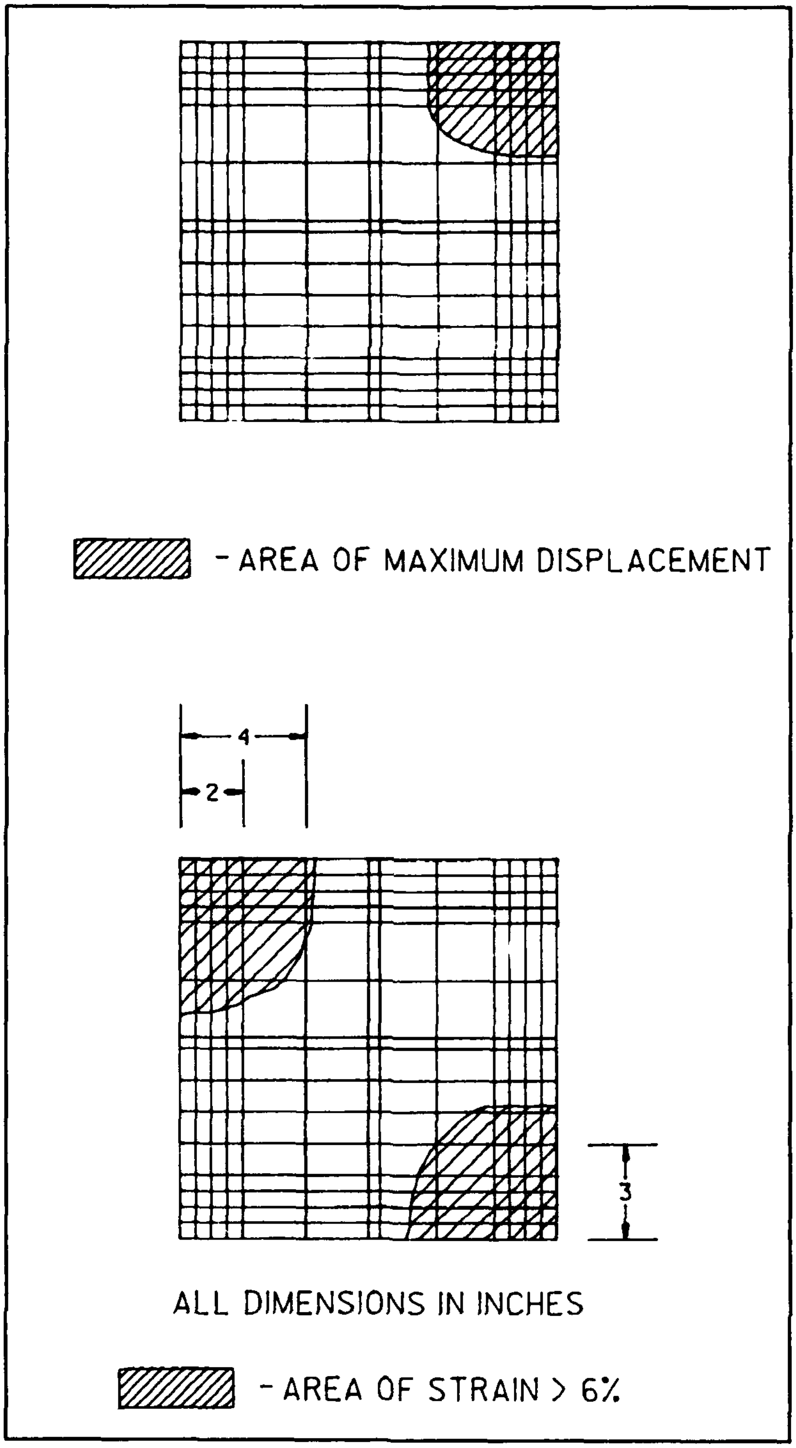


Figure 4.11 Location of Maximum Displacement and Strain for Case 3 Pressure Loading (a/b = 1.0, t= 3/8")

SECTION 5.0
FINDINGS AND RECOMMENDATIONS

5.1 FINDINGS

5.1.1 General

All test results in this report were generated from tests performed on full penetration butt welds fabricated in 3/8-inch ASTM A 36 steel, using E7014 Type electrodes. The underwater wet welds fabricated in this program were made in fresh water at a depth of 30 feet, and were fabricated using a wet welding procedure qualified to the standards of ANSI/AWS D3.6-89, for Type B welds.

1) Proper selection of weld filler material and welding procedures can be used to fabricate 3/8-inch thick underwater wet butt welds which meet the VT and RT requirements for ANSI/AWS D3.6 Type B welds.

2) The inspection procedures used for the underwater wet welds fabricated in this program indicated limited areas of rejectable slag inclusions in some wet welds. These areas were not repaired, as there was sufficient sound weld material for the preparation of fatigue test specimens. In a production setting, these defects would normally be detectable and repairable. These type of defects could be detected (through RT or UT or, to a lesser degree, MT of each weld layer) and repaired in production, where high quality is required. A joint design facilitating a two pass root layer would also reduce the tendency for entrapment of slag.

3) Results of all-weld-metal tensile tests from the underwater wet welds fabricated in this program were consistent with the results of previous studies, which indicate relatively high strength and tensile elongation values in the range of 6% to 8 %.

5.1.2 Fatigue Properties

All fatigue tests conducted in this program were performed in air using transverse weld specimens, subjected to cyclic axial tensile loading with a stress ratio of $R = 0.1$. Findings of this study indicate the following:

1) The fatigue test results for the underwater wet weld specimens without backing bars exhibited a low degree of scatter. This was demonstrated by the high correlation coefficient (0.9295) and the low standard error of estimate (0.136) calculated for the S-N curve generated from the data.

2) The S-N data for the underwater wet welds without backing bars indicates fatigue strength levels comparable to dry surface welds. Only one of the fifteen wet weld specimens tested experienced failure outside of the 95% confidence limits for the baseline dry surface weld data.

3) Based on limited testing at an applied stress ratio of 22.5 ksi, the mean fatigue life of underwater wet weld specimens with a backing bar was found to be about 50% lower than the mean fatigue life of specimens without backing bars. However, due to the limited number of tests and the nature of the results, a

general statement cannot be made with 95% confidence that the fatigue life of wet welds with backing bars will be different from the fatigue life of wet welds without backing bars. Additional testing would be required in order to make a valid statistical statement concerning the effect of a backing bar on the fatigue life of wet transverse butt welds subjected to axial loading.

5.1.3 Wet Weld Ductility

With regard to the relatively low tensile ductility of wet welds (6% to 8%), the following findings appear warranted from the results of the finite element analyses reported herein:

1) Butt welds in structural panels that traverse frames or bulkheads can develop weld metal tensile strains in excess of 6% when subjected to deflections typical of those encountered in service, as observed during ship surveys [31]. Underwater wet welds do not appear to have adequate weld metal ductility for these applications. However, underwater wet welds may be acceptable in these applications for temporary service, where the risk of sustaining significant plastic deformation and/or the consequence of weld failure are determined to be acceptable.

2) Butt welds in structural panels that are no closer than about 6" to frames or bulkheads should not develop weld metal tensile strains in excess of 6% under deflections typical of those encountered in service, as observed during ship surveys. Wet welds should have adequate tensile ductility for use in these applications.

3) For welding of structure other than plate panels (such as hull inserts, brackets, etc.), detailed analysis of the weld region should be performed to ensure that strains in excess of 6% in the wet weld will not be encountered under normal operating conditions.

5.2 RECOMMENDATIONS FOR FUTURE STUDY

The information in this study has been provided to further understanding of the potential for using underwater wet welding techniques for commercial ship applications. Taken with results of previous programs, it demonstrates that underwater wet welding should be considered for commercial ship applications. However, additional analysis and testing of underwater wet welds is needed prior to formal approval of underwater wet welding for use on commercial shipping. Therefore, it is recommended that the following tasks be undertaken:

1) Perform an underwater wet weld repair on a commercial ship structural panel or other detail, as per paragraph 5.1.3 above, obtain in-service data on structural performance. Provide for six month inspections and evaluation of the repaired area.

2) Based on the results of recommendation 1 above, prepare a comprehensive summary of justification and evidence to support ABS approval of underwater welding for commercial ships.

SECTION 6.0
ACKNOWLEDGEMENTS

The authors would like to express their appreciation to the individuals and organizations who provided assistance and direction during the course of this study. thanks are due to Mr. Thomas West of Third Party Plus, Mr. Thomas Reynolds and Chuck Mowry of Global Divers, and Mr. Frank Loss and Blaine Menke of Materials Engineering, Inc.

In addition, the authors would like to thank the members of the Ship Structure Committee Project Technical Committee for its direction and guidance throughout this effort. Special thanks go to Commander Michael Parmalee and his successor, Commander Stephen Sharpe, and to the Project Technical Committee Chairman, Mr. Eugene Mitchell.

Project Technical Committee Members

Cmdr. Michael Parmalee	U.S. Coast Guard
Cmdr. Stephen Sharpe	U.S. Coast Guard
Mr. Eugene Mitchell	Naval Sea Systems Command
Mr. Greg Woods	Naval Sea Systems Command
Mr. William Siekierka	Naval Sea Systems Command
Mr. Pete Czapiewski	Naval Sea Systems Command
Mr. Alexander Stavovy	National Research Council
Mr. Robert Waite	American Bureau of Shipping
Mr. Albert Attermeyer	American Bureau of Shipping
Mr. H. Paul Cojeen	U.S. Coast Guard

APPENDIX A
STEEL PLATE CERTIFICATION DOCUMENTS

082035 4PT 1-90

Gulf States Steel, Inc. GADSDEN, AL 35904-1935

150546

Z132-01

CONTROL CARD | REQ. JOB CONTRACT NO.

PURCHASE ORDER DATE: 04 09 90 | PURCHASE ORDER NO.: Q 0011 | RELEASE

CUSTOMER IDENTIFICATION

GSS ORDER NO.: DIST. G | NUMBER 14236 | MFG. 742 | ITEM NO.

CERTIFICATE OF TESTS

S 2 | OFFICE: EC | INVOICE DATE | INVOICE NUMBER: 742-10638

ACCOUNT NUMBER: 34604102 | TERMS: 30-3/4-10

SOLD TO:
HIGH STRENGTH STEEL INC
P O BOX 40606
HOUSTON TX 77240

SHIP TO:
HIGH STRENGTH
6605 N HOUSTON ROSSLYN
HOUSTON TX 77040

DATE SHIPPED	FROM	ROUTE/VEHICLE IDENTIFICATION	SHEET NO.
05 04 90	ALA CITY	CRESCO LINES	

I HEREBY CERTIFY THAT THE MATERIAL LISTED HEREIN HAS BEEN INSPECTED AND TESTED IN ACCORDANCE WITH THE METHODS PRESCRIBED IN THE GOVERNING SPECIFICATIONS AND BASED UPON THE RESULTS OF SUCH INSPECTION AND TESTING HAS BEEN APPROVED FOR CONFORMANCE TO THE SPECIFICATIONS.

LEONARD A. TROMAN
DIR. QUALITY ASSURANCE
AND METALLURGY

ITEM NO.	MATERIAL DESCRIPTION	P/C	QUANTITY SHIPPED
	PLATE CARBON ASTM A-36-88C MIL-S-2698-C GRD A CLASS U DTD 6/29/88 AMENDMENT 1 DTD 12/19/88		
03	.3750 X 96.0000 SHEARED EDGE X 480.0000 IN HT 7485729 3PCS	B	14703

QA APPROVED
5/8/90

CH C 25MX MN RPT P 040MX S 040MX SI RPT CU RPT NI RPT CR RPT MO RPT

MR YLD 36000 MIN TEN 58/71000 % ELONG MIN 2 IN 24 OR 8 IN 21

TI 3 T/R CA 1 T/R W/SHPMT ABS OUTSIDE INSP 4 MET SN TO ABS AT MILL

TOTAL WT. 26,955# PCS 6

CERTIFIED A TRUE COPY
OF THE ORIGINAL
RETAINED IN OUR FILE
HIGH STRENGTH STEEL, INC.
5/8/90
Q.A. DEPARTMENT

MILL TEST REPORTS FURNISHED
BY HIGH STRENGTH STEEL

DATE 10/25/90
CUSTOMER Global Divers
CUSTOMER P.O. GD400590
OUR W.O. NO. 3973

ANALYSIS

ITEM NO.	HEAT NO.	GRAIN	CARBON	MANG	PHOS	SUL	SIL	COPPER	NICKEL	CHROME	MOLY	VAN	Cb	AL
03	7485729		.17	0.48	.005	.017	.065	0.07	0.02	0.03	.01			

TEST RESULTS

ITEM NO.	HEAT NUMBER	TEST OR PIECE IDENTITY NO.	YIELD KSI	TENSILE STGTH. KSI	ELONG 2"	ELONG 8"	GALV. COATING	BEND TEST	HARD.	CHARPY IMPACT V NOTCH FT. LBS. AT °F TEST NO.	SPEC SIZE	1	2	3	AVG.
3	7485729		38	59		31.0		OK							

PAGE 2 LAST PAGE

BETHLEHEM STEEL CORPORATION
QUALITY ASSURANCE DEPARTMENT
REPORT OF TESTS AND ANALYSES

JRNS HARBOR PLANT

160120

MENT NO.	DATE SHIPPED	CAR OR VEHICLE NO.			
803-18910	10- 1-89	CSS-CHGO-BN	CR	715354	PAGE 5

SOLD TO
HIGH STRENGTH STEEL INC
BOX 40606
HOUSTON TX 77240

SHIP TO
HIGH STRENGTH STEEL INC
6605 N HOUSTON/ROSSLYN RD
NORTH HOUSTON TX 77091

SERIAL NUMBER	PAT. NO.	HEAT NUMBER	NO. PCS.	THICKNESS INCHES	WIDTH OR DIA. INCHES	LENGTH INCHES	WEIGHT POUNDS	YIELD POINT PSI	TENSILE STRENGTH PSI	ELONG. IN	ELONG. %
		821J13770	1	1	96	480	13068	44000	67300	8	31
		833J68540	1	1	96	480	13068	41400	65700	8	25
		833J68570	2	1	96	480	26136	40200 40000	65600 64500	8 8	25 26
		821J13770	1	3/4	120	480	12252	45100	67500	8	21
		843J68570	3	3/4	120	480	36756	47400 40200	69500 65600	8 8	27 25
		821J13780	4	3/4	96	480	39204	43000 43600	66100 65500	8 8	22 30

QUALITY STEEL MELTED & MANUFACTURED IN THE U. S. A.

PLATES - MIL-S -22698C GR B AMEND 1 CLASS U
MFST - LIFT MAX 20 TON UNLDG ON-PLATE CLAMP
CO# QA7035 GH 024-0469

MERCURY IN ANY FORM HAS NOT BEEN USED
IN THE PRODUCTION OF THIS ORDER
OUTSIDE INSPECTION BY AMERICAN BUREAU OF SHIPPING

89 CH90643 568

Q—QUENCH TEMPERATURE T—TEMPER TEMPERATURE N—NORMALIZE TEMPERATURE

WE HEREBY CERTIFY THAT THE MATERIAL DESCRIBED HEREIN HAS BEEN MADE BY THE BETHLEHEM STEEL CORP. TO THE APPLICABLE SPECIFICATION BY AN APPROVED PROCESS AND HAS BEEN TESTED IN ACCORDANCE WITH THE REQUIREMENTS OF THE AMERICAN BUREAU OF SHIPPING RULES FOR THE INSPECTION AND TESTING OF MATERIALS TO THE SATISFACTION OF THE SURVEYORS.

CHARPY IMPACT

SERIAL NUMBER	PAT. NO.	HEAT NUMBER	HARD	BEND	THICKNESS INCHES	TYPE	SIZE	DIR.	TEST TEMP.	ENERGY FT. LBS. 1	2	3	LAT. EXP. MILS 1	2	3

AMERICAN BUREAU OF SHIPPING
SURVEYOR
RICHARD T. McCOMBS
CHICAGO, ILL.

CHEMICAL ANALYSIS

HEAT NUMBER	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	B	Cb	N	McQUAID GRAIN SIZE
21J13770	.15	.98	.021	.007	.221	.021	.03	.04	.008							
33J68540	.16	.81	.016	.011	.207	.066	.03	.04	.008							
33J68570	.16	.87	.016	.009	.220	.029	.02	.03	.009							
~~3J68570~~	~~.16~~	~~.87~~	~~.016~~	~~.009~~	~~.220~~	~~.029~~	~~.02~~	~~.03~~	~~.009~~							
1J13780	.16	.74	.018	.011	.211	.019	.02	.03	.009							

PURCHASER'S COPY

TIFY THAT THE ABOVE RESULTS ARE A TRUE AND CORRECT COPY ECORDS PREPARED AND MAINTAINED BY BETHLEHEM IN COMPLI- WITH THE REQUIREMENTS OF THE SPECIFICATION CITED ABOVE.

SUPT. QUALITY ASSURANCE A.J. Barsophy PER WJK

APPENDIX B
WELDING PROCEDURE QUALIFICATION FORMS

DRY WELDING PROCEDURE QUALIFICATION FORM

Date 1/20/91 & 1/24/91

Test Depth N/A

Weld Identification AW-1A

Breathing Gas N/A

Water Temperature (Max.) N/A

(Min.) N/A

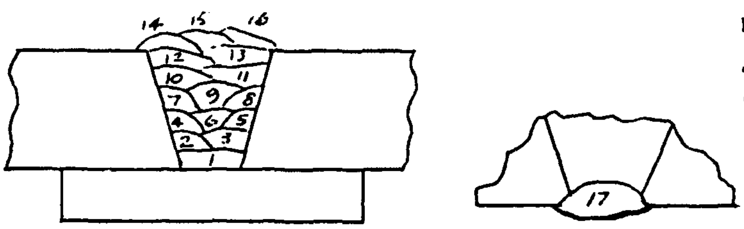
Water Pressure N/A

WELDING VARIABLES

Open Circuit Voltage	71
Arc Voltage (root)	25-30
Arc Voltage (fill)	25-30
Arc Voltage (capping)	25-30
Amps (root)	95-105
Amps (fill)	115-125
Amps (capping)	115-125
Base Metal	MIL-S-22698, GR.A
Base Metal Dimensions	3/8" x 2' x 3'
Carbon Equivalent	0.264
Filler Metal	*Broco Uncoated E7014 "Type"
Weld Process	SMAW
Filler Metal Size (root)	1/8"
Filler Metal Size (fill)	1/8"
Polarity	Reverse (Electrode Positive)
Position (V-up or V-down for vertical welding)	Vertical-Down, Except Root Vertical-Up
Alignment Clamp Used	Strongback
Start Time	1130 (Front Side) 0930 (Back Side)
Finish Time	1650 (Front Side) 0950 (Back Side)
Travel Speed (root)	4.6 IPM
Travel Speed (fill)	9.8-17.9 IPM
Time Btwn. Root & Fill	N/A
Power Source	400 Amp Miller Diesel Generator
Name of Welder/Diver	Robert S. Flinn

*Broco Sof Touch Without Waterproofing

JOINT DESIGN & SEQUENCE OF WELD PASSES



APPROXIMATE ROD ANGLE

Direction of welding: 90(R) 45 (Fill)

Transverse to the direction of welding: 0

Root Opening: 1/4"; Land: 0; Included Angle: 45°

GENERAL COMMENTS AND SPECIAL WELDING/PUDDLE CONTROL TECHNIQUES

1. Wedges used to bow plate 1/8" after completion of root pass.
2. Backing bar removed and backside ground and welded as shown.

DRY WELDING PROCEDURE QUALIFICATION FORM

Date 6/20/91 Test Depth N/A

Weld Identification AW-1B Breathing Gas N/A

Water Temperature (Max.) N/A

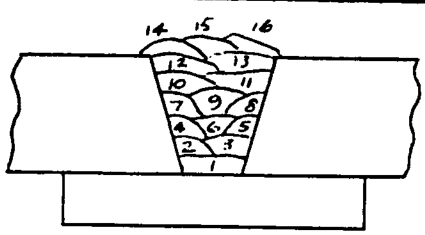
(Min.) N/A Water Pressure N/A

WELDING VARIABLES

Open Circuit Voltage	71
Arc Voltage (root)	25-30
Arc Voltage (fill)	25-30
Arc Voltage (capping)	25-30
Amps (root)	95-105
Amps (fill)	115-125
Amps (capping)	115-125
Base Metal	MIL-5-22698, GR A
Base Metal Dimensions	3/8" x 2' x 3'
Carbon Equivalent	0.264
Filler Metal	*Broco Uncoated E7014 "Type"
Weld Process	SMAW
Filler Metal Size (root)	1/8"
Filler Metal Size (fill)	1/8"
Polarity	Reverse (Electrode Positive)
Position (V-up or V-down for vertical welding)	Vertical-Down, Except Root Vertical-Up
Alignment Clamp Used	Strongback
Start Time	1130
Finish Time	1650
Travel Speed (root)	4.6 IPM
Travel Speed (fill)	9.8 IPM - 17.9 IPM
Time Btwn. Root & Fill	N/A
Power Source	400 Amp Miller Diesel Generator
Name of Welder/Diver	Robert S. Flinn

*Broco Sof Touch Without Waterproofing.

JOINT DESIGN & SEQUENCE OF WELD PASSES



APPROXIMATE ROD ANGLE

Direction of welding: 90(R); 45 (Fill)

Transverse to the direction of welding: 0

Root Opening: 1/4"; Land: 0; Included angle: 45°

GENERAL COMMENTS AND SPECIAL WELDING/PUDDLE CONTROL TECHNIQUES

1. Wedges used to bow plate 1/8" after completion of root pass.

WELDING PROCEDURE QUALIFICATION FORM

Date 1/22/91 & 1/23/91

Test Depth 30 FFW

Weld Identification WWMP-1

Breathing Gas Air

Water Temperature (Max.) 49F

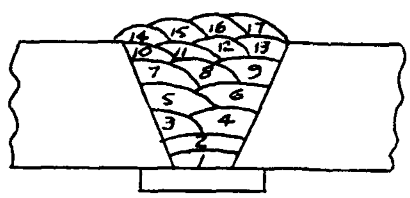
(Min.) 45F

Water Pressure 13.4 PSIG

WELDING VARIABLES

Open Circuit Voltage	71-73
Arc Voltage (root)	25-30
Arc Voltage (fill)	25-30
Arc Voltage (capping)	25-30
Amps (root)	150-155
Amps (fill)	150-165
Amps (capping)	150-165
Base Metal	MIL-S-22698, GR.B (ASTM A36 Backing Bar)
Base Metal Dimensions	3/4" x 12 x 14"
Carbon Equivalent	0.316
Filler Metal	Broco Sof Touch
Weld Process	SMAW
Filler Metal Size (root)	1/8"
Filler Metal Size (fill)	1/8"
Polarity	Straight (Electrode Negative)
Position (V-up or V-down for vertical welding)	Vertical-Down
Alignment Clamp Used	Strongback
Start Time	1607 (Root) 1344 (Fill)
Finish Time	1611 (Root) 1455 (Cap)
Travel Speed (root)	8.1 IPM
Travel Speed (fill)	7.1-10.9 IPM
Time Btwn. Root & Fill	N/A
Power Source	400 Amp Miller Diesel Generator
Name of Welder/Diver	Robert S. Flinn/Darryl Phillips

JOINT DESIGN & SEQUENCE OF WELD PASSES



Root Opening: 3/16"; Land: 0; Included Angle: 45°

APPROXIMATE ROD ANGLE

Direction of welding: 30-45

Transverse to the direction of welding: 0

GENERAL COMMENTS AND SPECIAL WELDING/PUDDLE CONTROL TECHNIQUES

1. Root pass made by D. Phillips. Remaining passes made by R. Flinn.

WELDING PROCEDURE QUALIFICATION FORM

Date 1/19/91 & 1/24/91

Test Depth 30 FFW

Weld Identification WW-1

Breathing Gas Air

Water Temperature (Max.) 49F

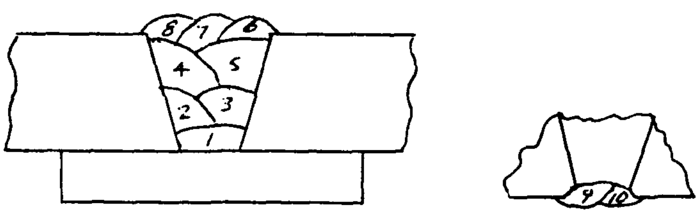
(Min.) 49F

Water Pressure 13.4 PSIG

WELDING VARIABLES

Open Circuit Voltage	69-71
Arc Voltage (root)	25-30
Arc Voltage (fill)	25-30
Arc Voltage (capping)	23-28
Amps (root)	150-160
Amps (fill)	150-165
Amps (capping)	140-155
Base Metal	MIL-5-22698, GR.A
Base Metal Dimensions	3/8" x 2' x 6'
Carbon Equivalent	0.264
Filler Metal	Broco Sof Touch
Weld Process	SMAW
Filler Metal Size (root)	1/8"
Filler Metal Size (fill)	1/8"
Polarity	Straight (Electrode Negative)
Position (V-up or V-down for vertical welding)	Vertical-Down
Alignment Clamp Used	Strongback
Start Time	1526 (Front Side) 1347 (Back Side)
Finish Time	2034 (Front Side) 1445 (Back Side)
Travel Speed (root)	6.8 IPM
Travel Speed (fill)	6.7-10.6 IPM
Time Btwn. Root & Fill	N/A
Power Source	400 Amp Miller Diesel Generator
Name of Welder/Diver	Robert S. Flinn

JOINT DESIGN & SEQUENCE OF WELD PASSES



APPROXIMATE ROD ANGLE

Direction of welding: 30-45

Transverse to the direction of welding: 0

Root Opening: 3/16"; Land: 0; Included Angle: 45°

GENERAL COMMENTS AND SPECIAL WELDING/PUDDLE CONTROL TECHNIQUES

1. Tacks made in groove in air. Segments of root pass made, and tacks ground out.
2. Wedges used to bow plate 3/16" after completion of root pass.
3. Backing bar removed and back side ground and welded as shown.

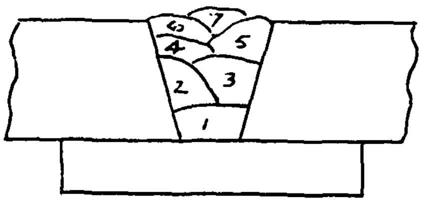
WELDING PROCEDURE QUALIFICATION FORM

Date	1/22/91 & 1/23/91
Test Depth	30 FFW
Weld Identification	WW-2
Breathing Gas	Air
Water Temperature (Max.)	50F
(Min.)	45F
Water Pressure	13.4 PSIG

WELDING VARIABLES

Open Circuit Voltage	71
Arc Voltage (root)	25-30
Arc Voltage (fill)	25-30
Arc Voltage (capping)	25-30
Amps (root)	150-155
Amps (fill)	150-160
Amps (capping)	150-160
Base Metal	MIL-S-22698, GR.A (ASTM A36 Backing Bar)
Base Metal Dimensions	3/8" x 2' x 6'
Carbon Equivalent	0.264
Filler Metal	Broco Sof Touch
Weld Process	SMAW
Filler Metal Size (root)	1/8"
Filler Metal Size (fill)	1/8"
Polarity	Straight (Electrode Negative)
Position (V-up or V-down for vertical welding)	Vertical-Down
Alignment Clamp Used	Strongback
Start Time	1438 (Root) 0920 (Fill)
Finish Time	1550 (Root) 1341 (Cap)
Travel Speed (root)	8.7 IPM
Travel Speed (fill)	6.6-9.8
Time Btwn. Root & Fill	N/A
Power Source	400 Amp Miller Diesel Generator
Name of Welder/Diver	Darryl Phillips/R.S. Flinn

JOINT DESIGN & SEQUENCE OF WELD PASSES



Root Opening: 3/16"; Land: 0; Included Angle: 45°

APPROXIMATE ROD ANGLE

Direction of welding: 30-45

Transverse to the direction of welding: 0

GENERAL COMMENTS AND SPECIAL WELDING/PUDDLE CONTROL TECHNIQUES

1. 1/2 hour delay in root pass due to equipment problems.
2. Root pass made by D. Phillips. Remaining passes made by R. Flinn.
3. Weldment was bowed approximately 3/16" after root pass using wedges.

APPENDIX C
MECHANICAL PROPERTY TEST REPORT

One (1) Test Weldment	Partek Job #19428-WT-008
Casde Corporation	Sheet 1 of 2
Attention: Tom West	28 February, 1991

BACKGROUND:

Casde Corporation provided one (1) 3/4" test weldment identified as WWMP-1. Partek Laboratories was to perform all-weld-metal tensile testing and bend testing.

TEST DATA:

Two all-weld-metal tensile test specimens were prepared and tested as follows:

Test Specimen Identification	T1
Test Specimen Size	0.350"
Ultimate Tensile Strength	82,900 psi
0.2% Offset Yield Strength	77,100 psi
Elongation in 1.4"	7.4%
Reduction of Area	13.2%

Test Specimen Identification	T2
Test Specimen Size	0.350"
Ultimate Tensile Strength	79,600 psi
0.2% Offset Yield Strength	74,200 psi
Elongation in 1.4"	6.4%
Reduction of Area	10.5%

Two (2) side bend specimens were prepared and tested using a 3" diameter plunger. Each specimen exhibited one (1) - 1/16" tear.

MACRO-EXAMINATION:

Later a specimen of a 3/8" test weldment was provided that exhibited slag inclusions. The specimen was ground, polished and etched with 3% Nital. Reference photographs are attached to this report.

Respectfully submitted,

R L Sutton

R.L. Sutton, P.E.
Senior Staff Metallurgist
REG. NO. 24078

Photomacrograph showing weld cross-section. The slag inclusion are typical of those encountered.

Certified By:

R.L. Sutton, P.E.
Senior Staff Metallurgist
REG. No. 24078

REFERENCES

1. Fulton, "Progress in Underwater Welding", *Ocean Industry*, 1986.

2. "AWS D3.6-89; Specification for Underwater Welding", American Welding Institute, 1989,

3. West and Mitchell, "Evaluation of Commercially Available Wet Welding Electrodes for Potential Repair of U.S. Navy Ships", SNAME Transactions, 1987.

4. West, Mitchell, and Lindberg, "Wet Welding Electrode Evaluation for Ship Repair", presented at the 70th Annual AWS Meeting, 1989.

5. Dexter, Norris, Schick, and Watson, "Performance of Underwater Weldments", SSC-335, 1990.

6. Matlock, Edwards, Olson, and Ibarra,"An Evaluation of the Fatigue Behavior in Surface, Habitat, and Underwater Wet Welds", Proceedings of the 2nd International Conference on Offshore Welded Structures, 1982.

7. "Effects of Sea Water on the Fatigue Crack Propagation Characteristics of Welds for Offshore Structures", Matlock, Edwards, Olson, and Ibarra, *Journal of Materials Engineering*, 1987.

8. Committee III.1 Report, Proceedings of the Seventh International Ships Structure Congress, 1979.

9. Munse, "Fatigue of Weldments - Tests, Design And Service", ASTM 1978.

10. Munse, "Fatigue of Welded Steel Structures", *Welding Research Council*, 1964.

11. Masubuchi, Analysis of Welded Structures, International Series on Materials Science and Technology, Volume 33.

12. Munse, Wilbur, Tellalian, Nicoll, and Wilson, "Fatigue Characterization of Fabricated Ship Details for Design", SSC-318, 1984.

13. Wilson, "Fatigue Tests of Welded Joints in Structural Steel Plates", *The Welding Journal*, 1941.

14. Polland and Cover, Fatigue of Steel Weldments.

15. Ross, Experiments for the Determination of the Influence of Residual Stresses on the Fatigue Strength of Structures", Welding Research BWRA, 1950.

16. Gooch, "Properties of Underwater Welds, Part 2 - Mechanical Tests", *Metal Construction*, 1983.

17. Wilson, "The Fatigue Strength of Various Types of Butt Welds Connecting Steel Plates," University of Illinois EESB Number 384.

18. Radziminski, "Fatigue Data Bank and Data Analysis Investigation", University of Illinois, 1973.

19. MIL-E-0022200/10A, "Electrodes, Welding, Mineral Covered, Iron Powder, Low-Hydrogen Medium, High Tensile and Higher Strength Low Alloy Steels"

20. "AWS A5.5-81; Specification for Low Alloy Steel Covered Arc Welding Electrodes", American Welding Society, 1981.

21. MIL-E-23765/2D, "Electrodes and Rods, Welding, Bare, Solid, or Alloy Cored, Low Alloy Steel"

22. MIL-S-22698B, "Steel Plate and Shapes, Weldable Ordinary Strength and Higher Strength: Hull Structural"

23. Rules for Building and Classing Steel Vessels, American Bureau of Shipping, 1979.

24. MIL-STD-248C, "Welding and Brazing Procedure and Performance Qualification".

25. MIL-STD-271F, " Nondestructive Testing Requirements for Metals".

26. NAVSHIPS 0900-LP-003-8000, "Surface Inspection Acceptance Standards for Metals".

27. NAVSHIPS 0900-LP-003-9000, "Radiographic Acceptance Standards for Production and Repair Welds".

28. ANSI/AWS B4.0-85, "Standard Methods for Mechanical Testing of Welds".

29. "ASTM E466-8; Standard Practice for Conducting Constant Amplitude Axial Fatigue Tests of Metallic Materials", ASTM Standards, 1990.

30. ASTM E739-8; Statistical Analysis of Linear or Linearized Stress-Life and Strain-Life Fatigue Data", ASTM Standards, 1990.

31. Jennings, Grubbs, Zanis, and Raymond, "Inelastic Deformation of Plate Panels", SSC-364, 1991.

32. COSMOS/M User Guide, Version 1.65 Fourth Edition, published by Structural Research and Analysis Corporation, 1992.

BIBLIOGRAPHY

1. Reemsnyder, "Development and Application of Fatigue Data for Structural Steel Weldments", ASTM STP 648, 1978."Fatigue Tests on 1/2-Inch Thick Transverse Butt Welds Containing Slag Inclusions", Newman and Gurney, *British Welding Journal*, 1964.

2. "Further Fatigue Tests of 1 1/2-Inch Thick Butt Welds Containing Slag Inclusions", Harrison, *British Welding Journal*, 1968.

3. <u>Fatigue Strength of Welded Structures</u>, Richards, 1969.

4. "Properties of Underwater Welds, Part 2 - Mechanical Tests", Gooch, *Metal Construction*, 1983.

5. "Weld Profile and Plate Thickness Effects in Fatigue as Applicable to Offshore Structures", American Petroleum Institute, 1987.

6. "Fatigue of Selected High Strength Steels in Sea Water", American Petroleum Institute, 1985.

7. <u>Machinery's Handbook, 23rd Edition</u>, Oberg, 1989.

8. <u>ASTM STP 648; Fatigue Testing of Weldments</u>, Hoeppner, ASTM, 1977.

9. "Corrosion Fatigue of Welded Carbon Steel for Application to Offshore Structure", American Petroleum Institute, 1977."

10. "Shallow Underwater Welding", Ibarra, presented to the International Workshop on Quality in Underwater Welding of Marine Structures, 1985.

11. <u>Atlas of Fatigue Curves</u>, Boyer, 1986.

12. Mechanical Metallurgy, Dieter, 1967.

13. "State-of-the-Art for Applying Wet and Water-Backed Welding Procedures to the Repair or Modification of Marine Structures, Phase I Progress Report", SSC 1283, 1983.

14. Stevenson, "Offshore Options Reviewed", *Welding and Metal Fabrication*, 1983.

15. Jordan and Cochran, "In-Service Performance of Structural Details", SSC-272, 1978.

16. Jordan and Cochran, "Further Survey of In-Service Performance of Structural Details", SSC-294, 1980.

Project Technical Committee Members

The following persons were members of the committee that represented the Ship Structure Committee to the Contractor as resident subject matter experts. As such they performed technical review of the initial proposals to select the contractor, advised the contractor in cognizant matters pertaining to the contract of which the agencies were aware, and performed technical review of the work in progress and edited the final report.

Eugene Mitchell	Naval Sea Systems Command
Peter M. Czapiewski	Naval Sea Systems Command
Eric P. Lindberg	Naval Sea Systems Command
Fred Seibold	Maritime Administration
Al Attermeyer	Military Sealift Command
Bill Hanzlak	American Bureau of Shipping
David Reznik	American Bureau of Shipping
CDR Larry Doyle	U. S. Coast Guard
Ash Chatterjee	U. S. Coast Guard
Ken Bitting	U. S. Coast Guard
Dr. Santiago Ibarra Jr.	Amoco Corporation
Mr. William Siekierka	Naval Sea Systems Command, Contracting Officer's Techical Representative
Mr. Alex Stavovy Dr. Robert Sielski	National Academy of Science, Marine Board Liaison
CDR Mike Parmelee CDR Steve Sharpe	U.S. Coast Guard, Executive Director Ship Structure Committee

*U.S. G.P.O.:1994-301-717:80573

COMMITTEE ON MARINE STRUCTURES

Commission on Engineering and Technical Systems

National Academy of Sciences – National Research Council

The COMMITTEE ON MARINE STRUCTURES has technical cognizance over the interagency Ship Structure Committee's research program.

Peter M. Palermo Chairman, Alexandria, VA
Subrata K. Chakrabarti, Chicago Bridge and Iron, Plainfield, IL
John Landes, University of Tennessee, Knoxville, TN
Bruce G. Collipp, Marine Engineering Consultant, Houston, TX
Robert G. Kline, Marine Engineering Consultant, Winona, MN
Robert G. Loewy, NAE, Rensselaer Polytechnic Institute, Troy, NY
Robert Sielski, National Research Council, Washington, DC
Stephen E. Sharpe, Ship Structure Committee, Washington, DC

LOADS WORK GROUP

Subrata K. Chakrabarti Chairman, Chicago Bridge and Iron Company, Plainfield, IL
Howard M. Bunch, University of Michigan, Ann Arbor, MI
Peter A. Gale, John J. McMullen Associates, Arlington, VA
Hsien Yun Jan, Martech Incorporated, Neshanic Station, NJ
John Niedzwecki, Texas A&M University, College Station, TX
Solomon C. S. Yim, Oregon State University, Corvallis, OR
Maria Celia Ximenes, Chevron Shipping Co., San Francisco, CA

MATERIALS WORK GROUP

John Landes, Chairman, University of Tennessee, Knoxville, TN
William H Hartt, Florida Atlantic University, Boca Raton, FL
Horold S. Reemsnyder, Bethlehem Steel Corp., Bethlehem, PA
Barbara A. Shaw, Pennsylvania State University, University Park, PA
James M. Sawhill, Jr., Newport News Shipbuilding, Newport News, VA
Bruce R. Somers, Lehigh University, Bethlehem, PA
Jerry G. Williams, Conoco, Inc., Ponca City, OK

SHIP STRUCTURE COMMITTEE PUBLICATIONS

SSC-354 Structural Redundancy for Discrete and Continuous Systems by P. K. Das and J. F. Garside 1990

SSC-355 Relation of Inspection Findings to Fatigue Reliability by M. Shinozuka 1989

SSC-356 Fatigue Performance Under Multiaxial Load by Karl A. Stambaugh, Paul R. Van Mater, Jr., and William H. Munse 1990

SSC-357 Carbon Equivalence and Weldability of Microalloyed Steels by C. D. Lundin, T. P. S. Gill, C. Y. P. Qiao, Y. Wang, and K. K. Kang 1990

SSC-358 Structural Behavior After Fatigue by Brian N. Leis 1987

SSC-359 Hydrodynamic Hull Damping (Phase I) by V. Ankudinov 1987

SSC-360 Use of Fiber Reinforced Plastic in Marine Structures by Eric Greene 1990

SSC-361 Hull Strapping of Ships by Nedret S. Basar and Roderick B. Hulla 1990

SSC-362 Shipboard Wave Height Sensor by R. Atwater 1990

SSC-363 Uncertainties in Stress Analysis on Marine Structures by E. Nikolaidis and P. Kaplan 1991

SSC-364 Inelastic Deformation of Plate Panels by Eric Jennings, Kim Grubbs, Charles Zanis, and Louis Raymond 1991

SSC-365 Marine Structural Integrity Programs (MSIP) by Robert G. Bea 1992

SSC-366 Threshold Corrosion Fatigue of Welded Shipbuilding Steels by G. H. Reynolds and J. A. Todd 1992

SSC-367 Fatigue Technology Assessment and Strategies for Fatigue Avoidance in Marine Structures by C. C. Capanoglu 1993

SSC-368 Probability Based Ship Design Procedures: A Demonstration by A. Mansour, M. Lin, L. Hovem, A. Thayamballi 1993

SSC-369 Reduction of S-N Curves for Ship Structural Details by K. Stambaugh, D. Lesson, F. Lawrence, C-Y. Hou, and G. Banas 1993

SSC-370 Underwater Repair Procedures for Ship Hulls (Fatigue and Ductility of Underwater Wet Welds) by K. Grubbs and C. Zanis

SSC-371 Establishment of a Uniform Format for Data Reporting of Structural Material Properties for Reliability Analysis by N. Pussegoda, L. Malik, and A. Dinovitzer

None Ship Structure Committee Publications – A Special Bibliography